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GETAWAY TETHER EXPERIMENT (GATE)

A FREE FLYING TETHER EXPERIMENT

{NASA-CR-179912} GETAWAY TETHER EXPERIMENT

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{GATE}: A FREE FLYING TETHER EXPERIMENT

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A Final Report

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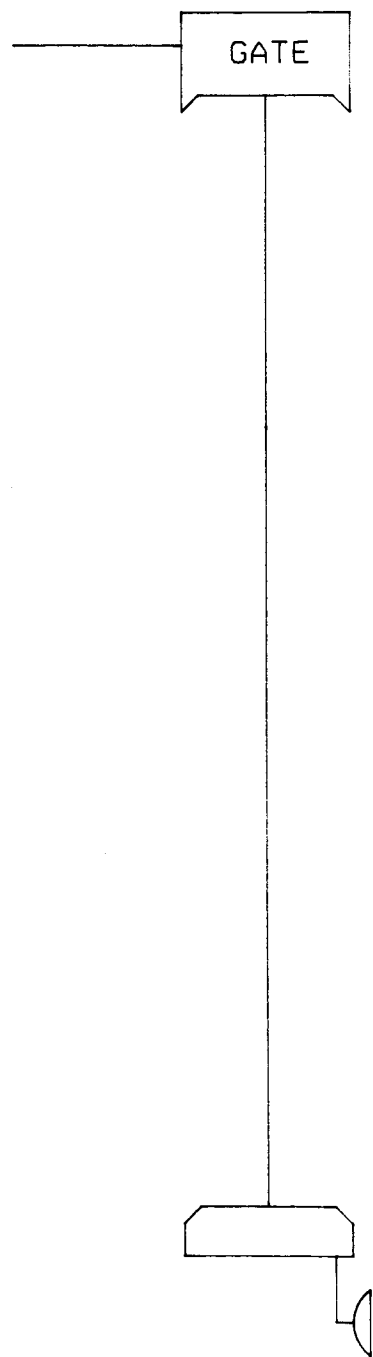
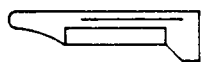
By

Michael Greene, PH.D.
Assistant Professor
University of Alabama in Huntsville
Huntsville, Alabama 35899

December 1986

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OBJECTIVES

Orbital reboost and power generation using electrodynamic tethers has been suggested as a means of increasing the operational flexibility and orbital lifetime of satellites¹. Excess energy generated by solar arrays can be stored as orbital energy and later extracted from the orbit during peak power demands. The GATE experiment will demonstrate this practical tether application and will measure the dynamic circuit impedance. The small forces generated will scale to the small size of GATE so that observable orbital changes will occur. The dynamic impedance measurements complement those of the Tethered Satellite System (TSS) first flight and may help plan the second TSS electrodynamic mission.

Micrometeoroid hazards to space tethers have been the subject of uncertainty because prior measurements on flux was relative to flat plates and hypervelocity impact tests were performed on flat plates. Application of these data to tethers involves extrapolation in dimensions and in damage mechanics. A short series of tests performed by Martin Marietta Aerospace² in support of the TSS was performed on stainless steel and woven Kevlar under no tension. Extrapolation of the data to tensioned Kelvar is questionable. Additional tests are scheduled by MMA for the fall of 1986 to assess hypervelocity impacts on tensioned tethers. These tests, while addressing the damage mechanisms, do not answer the flux issues. A long duration exposure in space can provide this data. Shock waves generated by micrometeoroid impacts on a tether are expected to have unique signatures. These waves and ensuing vibrations are detected, analyzed, and the resulting data is transmitted to ground. These data will also be of value in assessing damage to tension cables in large space structures and to electrical or data transmission lines.

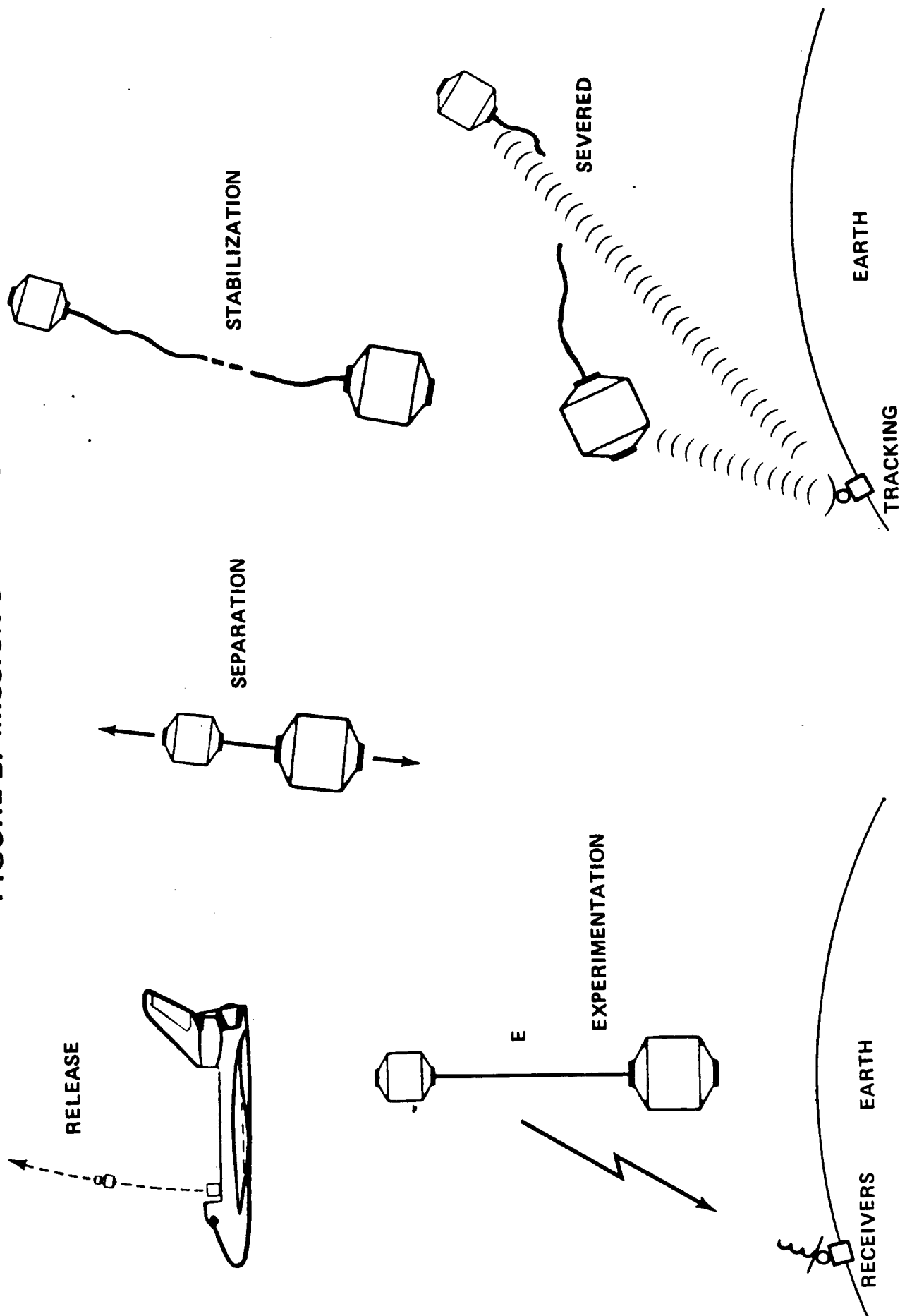
GET AWAY TETHER EXPERIMENT (GATE) OBJECTIVES

- **ELECTRODYNAMIC TECHNOLOGY**
 - DEMONSTRATE USEFUL POWER GENERATION
 - DEMONSTRATE OBSERVABLE ORBIT BOOST
- **MICROMETEOROID HAZARD TO TENSION MEMBERS**
- **RADIO FREQUENCY PROPAGATION**
- **RADAR CROSS SECTION OF LONG WIRES**

The GATE capability to excite ultra low frequency radio waves is not equal to that of the TSS, but GATE can provide additional data. The efficiency of the short antenna compared to that of the long antenna (TSS) is of interest for communications purpose. A second radio objective, telemetry reception by radio amateurs, promotes worldwide interest in space. The flight of Get Away Special 007 by the Alabama Space and Rocket Center³ was extremely successful in this regard. The mode of transmission is a subset of the packet radio protocol now in a period of explosive growth in interest. Low cost terminals are available and are in wide use in the United States and will be world wide. Using the GAS 007 experience, coverage can be expected throughout the Americas, Japan, Europe, and Australia. The data mode and power level will allow unattended reception on the ground. Near real time data is possible using amateur radio.

Although much theory exists for calculating the radar cross section of long wires, the theory has ignored the effects of resistance. This introduces much error in grazing incidence calculations. Also, the effects of reflections from long wires on radar processors has not been addressed in the open literature. The objective to measure these with the rendezvous radar is of interest to NASA in future Shuttle operations near space tethers. This is of interest in detecting and avoiding tethers. Also of interest is the ability to discriminate the satellites at the ends of the tether. Tests of the rendezvous radar at White Sands in 1985 for the TSS program⁴ showed negligible interference by the electrodynamic tether. However, tether straightness was an issue in the tests and the measurements were made only at angles expected in the TSS flight. Orbital flights appear to be the only way very long wires can be supported in radio frequency "free space" for radar measurements

FIGURE 2. MISSION SEQUENCE



MISSION SEQUENCE

The accompanying figure show the mission sequence for GATE in general. After release from the GAS cannister the satellites will separate using a spring induced initial velocity and then the gravity gradient during later phases. The next phase is stabization using the control laws developed. Experimentation consists of each of the objectives.

Different orientations are required for GATE for the charging experiments and for the electro-boost experiments. Using the larger satellite (mother) as an electron collector and the smaller (daughter) as an electron emitter, the mother must be in the higher orbit for charging and in the lower orbit for boosting. This necessitates 'flipping' the configuration between these two experiments.

GATE

MISSION SEQUENCE

1. INITIAL DEPLOYMENT
2. FLIP & RE-DEPLOYMENT AS REQUIRED
3. ELECTROBOOST I (15 DAY)*
4. FLIP & RE-DEPLOYMENT
5. CHARGING EXPERIMENT I *
(15 - 30 DAY)
6. FLIP & RE-DEPLOYMENT
7. ELECTROBOOST II (15 DAY)*
8. FLIP & RE-DEPLOYMENT
9. CHARGING EXPERIMENT II*
(15 - 30 DAY)
10. RE-ENTRY

* ALSO RADAR CROSS SECTION, RADIO
PROPAGATION AND METEORITE IMPACT
EXPERIMENTS

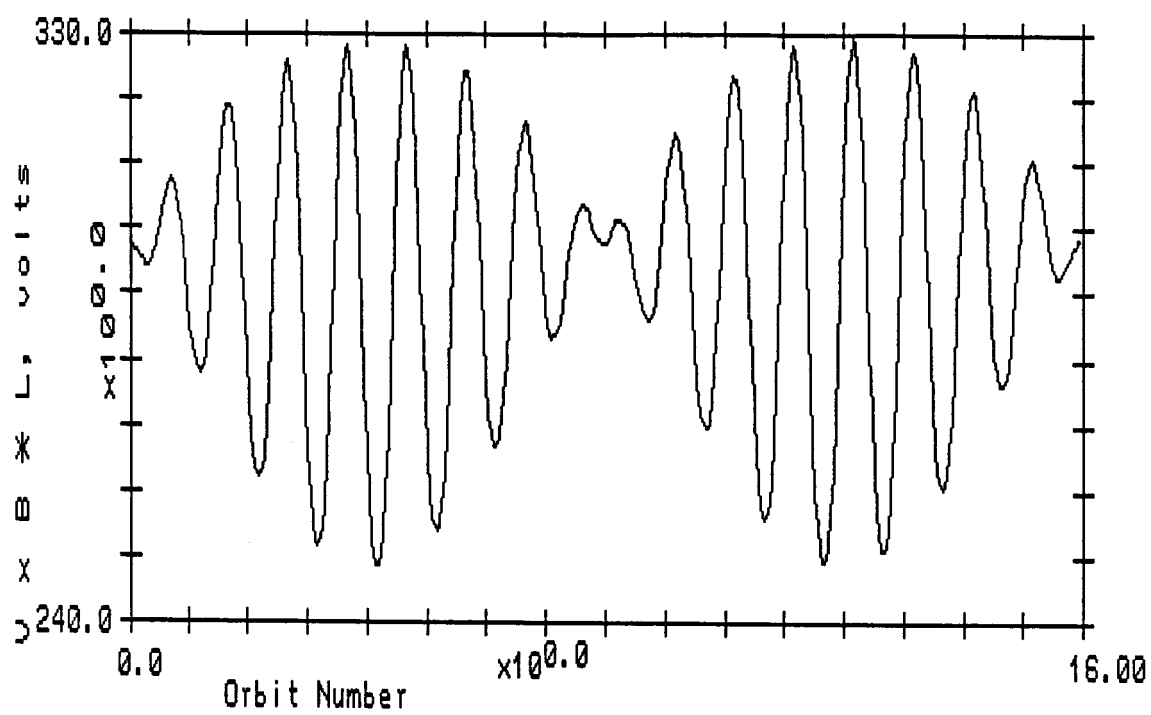
The detail mission sequence for a possible 90 day mission is given. After initial deployment, the orientation of the system will be sensed from the polarity of the induced voltage. If the mother is not in the down position, the system will be 'flipped' and redeployed. A 15 day electro-boost experiment is envisioned that will increase the orbit by 7- 10 %. The system will then be 're-flipped' and a charging experiment will ensue. After a recharging period of up to 30 days the system will be 're-flipped' again and a second boost experiment is planned. This will be followed by another 'flip' maneuver and another charging experiment.

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GETAWAY TETHER EXPERIMENT
(GATE)
ELECTRODYNAMICS

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VBL for 28 degree Inclination



GATE ELECTRODYNAMICS

The GATE, when fully deployed and stabilized in local vertical, is a conductor moving through the Earth's magnetic field, and a nonelectrostatic EMF is developed along the length of the tether due to the $V \times B \cdot L$ effect. The length of the tether is 1000 m, its velocity will be about 7740 m/s, and a nominal value of magnetic field strength at 300 km altitude is 0.45 Gauss. Thus, when the tether orientation, velocity, and magnetic field are mutually perpendicular, the developed EMF has a maximum value of 350 V. However, due to orbital inclination and magnetic anomalies, this EMF is expected to vary as much as 50%⁹. This is a plot of the induced potential, VBL , as a function of time for an orbit with a 28° inclination for the 1 km. tether of the GATE.

METHODS OF PLASMA CONTACT

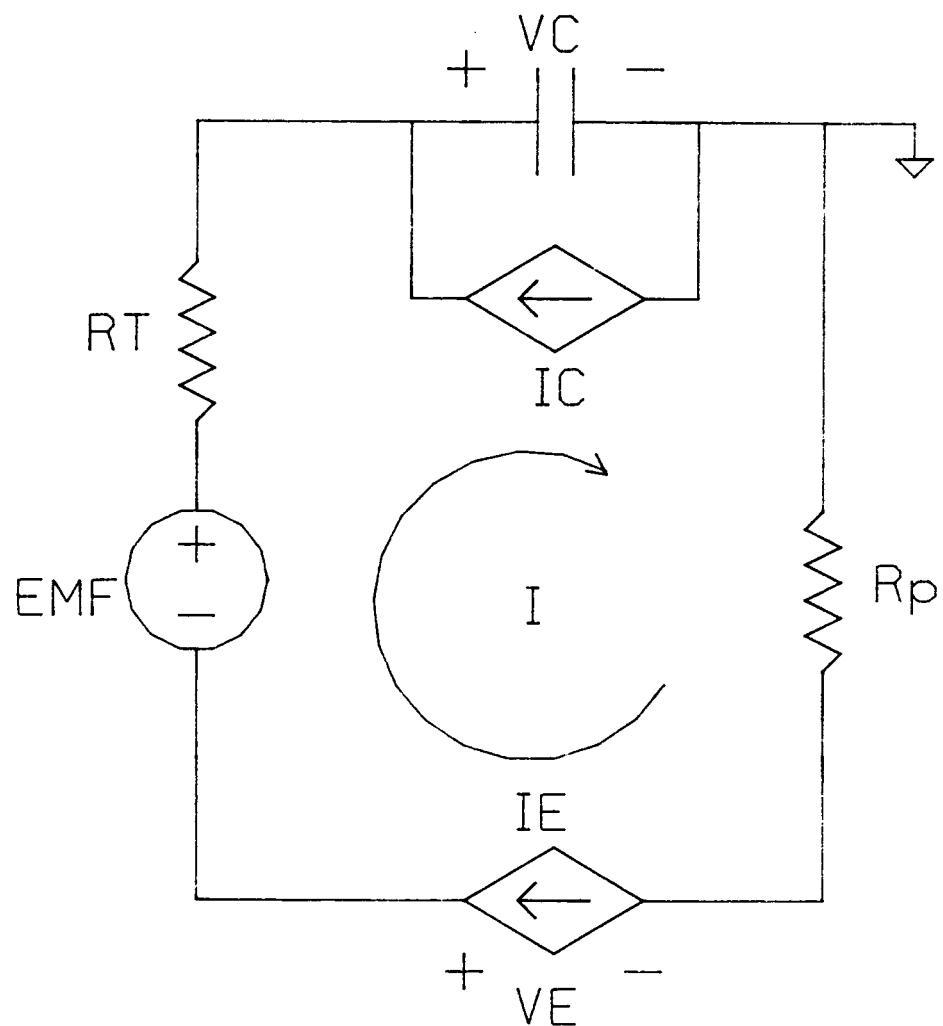
- o PASSIVE: PARTICLE COLLECTION
 - ADV: NO MASS PENALTY
 - NO ENERGY PENALTY
 - LOWEST COST AND COMPLEXITY
 - DIS: CURRENT PROPORTIONAL TO SURFACE AREA
 - ADDITIONAL SURFACE AREA INCREASES DRAG
 - CURRENT DEPENDENT ON PARTICLE DENSITY
- o ACTIVE: ELECTRON EMISSION
 - ADV: NO MASS PENALTY
 - LOW COST; HIGH CURRENT POSSIBLE
 - LESS DEPENDENCE ON PARTICLE DENSITY
 - DIS: ENERGY PENALTY IF INTERNAL POWER USED
 - POSSIBLE SPACE CHARGE LIMITATION
- o ACITVE: HOLLOW CATHODE PLASMA CONTACTOR
 - ADV: LOW PLASMA CONTACT VOLTAGE DROP
 - HIGH CURRENT POSSIBLE
 - LITTLE DEPENDENCE ON PARTICLE DENSITY
 - DIS: HIGHEST COST
 - MASS PENALTY
 - ENERGY PENALTY

To cause a current to flow through the tether, a means must be provided for electrical conduction through the ionospheric plasma. Plasma contact must occur at the mother or daughter subsatellites with an insulated tether. Three methods of plasma contact have been examined. A passive method of plasma contact is particle collection on the surfaces of the subsatellites. No internal energy or mass is expended, and this method is certainly lowest in cost and complexity. One of the disadvantages of plasma contact made solely through particle collection is the magnitude of current realizable. Electrons may be trapped on the surface of the subsatellites in relatively large quantities yet the transfer of positive charge limits the current to microamps¹⁰. Larger current values are possible with larger collecting surface but provision must be made to limit aerodynamic drag.

An alternative to collection of positively charged ions is the emission of electrons. Thermionic emission is a proven technology and has no mass penalty. A high current is possible with such a configuration, but there is an energy penalty for heating the filament. Either internal electrical energy must be expended, or if solar energy may be harnessed, provision must be made to direct the collecting surface at the Sun. Previous experiments with electron emitting spacecraft such as ATS-5 have shown that for this method of plasma contact to be effective, the charging of the satellite surface must be taken into account.¹¹

Perhaps the most effective method of plasma contact is the hollow cathode¹². The hollow cathode creates its own plasma and clamps the potential of the subsatellite to that of the surrounding environment. High currents are possible, and dependence on ambient ionization level is minimized. The disadvantages to the hollow cathode are three-fold: higher cost, mass penalty, and energy penalty for heating the ionization chamber.

GATE ELECTRODYNAMIC EQUIVALENT CIRCUIT



R_T = TETHER RESISTANCE + LOAD RESISTANCE

$EMF = (V \times B \cdot L) + \text{APPLIED VOLTAGE}$

Once plasma contact has been established, the GATE will execute two electrodynamic experiments: electroboost and system recharge. The simplified equivalent circuit of the tether-plasma system has a series resistance, a source of EMF, the nonlinear plasma contact relationships, and a circulating current. This circuit can be used for either the Alven generator or Alven motor configuration simply by changing the EMF source. In the generator configuration, the EMF source is only the induced VBL. In the engine configuration, the EMF source is $V_{\text{applied}} - VBL$.

For the GATE to be configured as an Alven generator, the series resistance would be the sum of tether resistance, a load impedance, and the impedance of the plasma between the two contactors. The EMF is just $v \times B \cdot L$ and the power extracted from the orbit is the product of the current flowing in the tether and the induced EMF. The product $I^2 R_L$ represents the conversion of part of the orbital energy into useful electrical energy.

The other configuration for the GATE is the Alven Engine. Stored electrical energy is expended to increase orbital energy and, thus, increase the orbital altitude of the GATE. In this case, the total EMF of the system is the sum of $V \times B \cdot L$ and an applied voltage inside the mother subsatellite. The polarity of the applied voltage must be opposite to the induced EMF and its magnitude must be greater for electroboost to be successful. The series resistance of the applied voltage source replaces the load impedance in the electroboost configuration and the power gained by the orbit would be the power expended by the voltage source minus the losses in the tether and the plasma contact.

GATE . ELECTRODYNAMICS

- EMF DEVELOPED ACROSS LENGTH OF TETHER = $\vec{v} \times \vec{B} \cdot \vec{L}$
- GATE VELOCITY = 7740 m/s AT 300 km ALT.
- MAGNETIC FIELD MAGNITUDE APPROX. 0.45 GAUSS
- ORBITAL INCLINATION AND MAGNETIC ANOMALIES VARY
HORIZONTAL MAGNETIC COMPONENT BY MORE THAN 25%
- PLASMA CONTACT AT ENDS OF TETHER:
CIRCUIT COMPLETION THROUGH PLASMA NOT WELL DEFINED
- EFFICIENCY OF PLASMA CIRCUIT CONTACT DEPENDS ON
IONIZATION LEVEL AND PARTICLE TEMPERATURE:
BOTH VARY WIDELY FROM DAY TO NIGHT

It must be stressed that the circuit completion through the plasma is still not well defined¹³. Many studies on the subjects of particle collection and plasma impedance¹³⁻¹⁸ have been done in the last two decades but little experimental data has been collected. It is known that the magnitude of the current in the GATE system will be a nonlinear function of: Ionization level of the plasma; Thermal energy of the ions and electrons; Magnetic field strength and orientation; Tether velocity and orientation; Total series impedance of the tether-plasma circuit; and, Plasma contactor potential and temperature. The ionization level of the plasma and thermal energy of ions and electrons in the ionosphere vary from day to night and with level of solar activity. It has been hypothesized that the plasma impedance between the contactors will be very small: on the order of one ohm¹⁸.

Current density relationships for the thermionic emitter:

$$V \geq 0: J = K T^2 \exp[-(\phi + eV)/kT]$$

$$V < 0: J = K T^2 \exp[(-\phi + \sqrt{e^3 E / 4\pi\epsilon})/kT]$$

Current - voltage relationship for hollow cathode:

$$I = -0.00589 + 0.03884 \exp(-0.07541 V)$$

(Source: experimental data from NASA contract TM-88850,
M. Patterson and P. Wilbur)

Current density relationships for the collecting subsatellite:

For negative collector potential:

$$I = A [J_i + J_e \exp(-|N_{ep}|)]$$

For positive collector potential:

$$I_0 = A [J_e + J_i \exp(-|N_{ep}|)]$$

Dobrowolny - Janve Model:

$$I = 0.64 I_0 ((|e| V_{ep} / k T_e) (L_d/a)^{4/3})^{6/7}$$

Parker - Murphy Model:

$$I = I_0 (1 + 2 \sqrt{V_{ep} / V_0})$$

where:

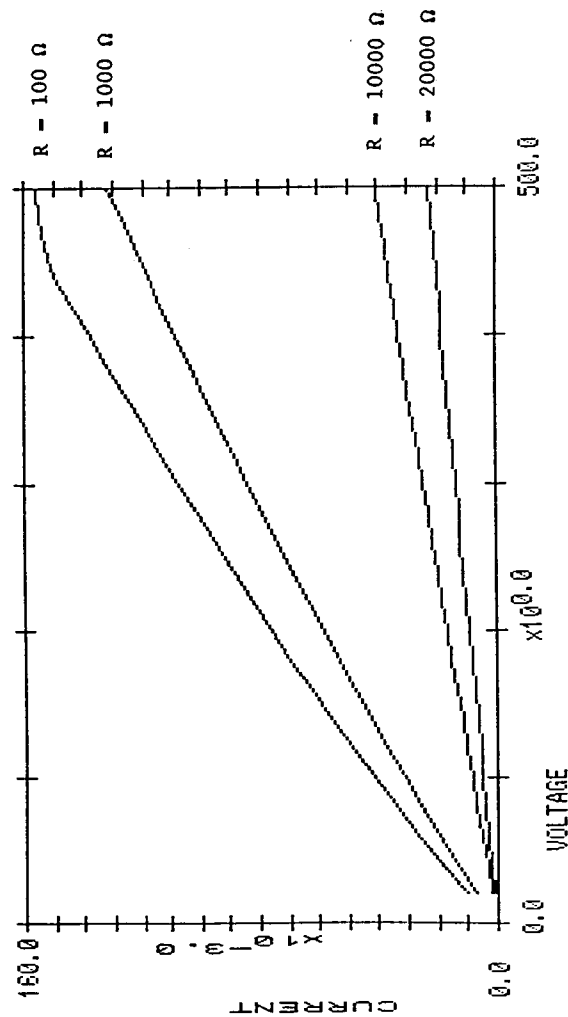
- V_{ep} = potential of electrode with respect to plasma
- a = dimension of collecting electrode
- A = surface area of collecting electrode
- T_e = electron temperature
- k = Boltzmann's constant
- N_e = electron density of plasma
- v_{the} = electron thermal velocity = $\sqrt{2 k T_e / m_e}$
- K = 120 ampere/cm² °K²
- T = filament temperature, °Kelvin
- ϕ = emitter work function
- V = potential of filament
- e = electron charge, 1.602×10^{-19} C
- ϵ = permittivity of region around filament
- E = electric field at filament (V / r_{fil})
- V_0 = $178 a^2 (B / 0.45)^2$
- N_{ep} = $|e| V_{ep} / k T_e$
- J_i = $0.5 N_i Z_i |e| v / \pi$
- J_e = $0.25 N_e e v_{the}$

For the purposes of the missions of the GATE, two models of particle collection will be considered. The first by Parker and Murphy¹² will be considered as the worst case (lowest current) and a model based on Dobrowolny and Janve¹³ will be considered as the best case. The use of these two models will bracket the performance of the GATE.

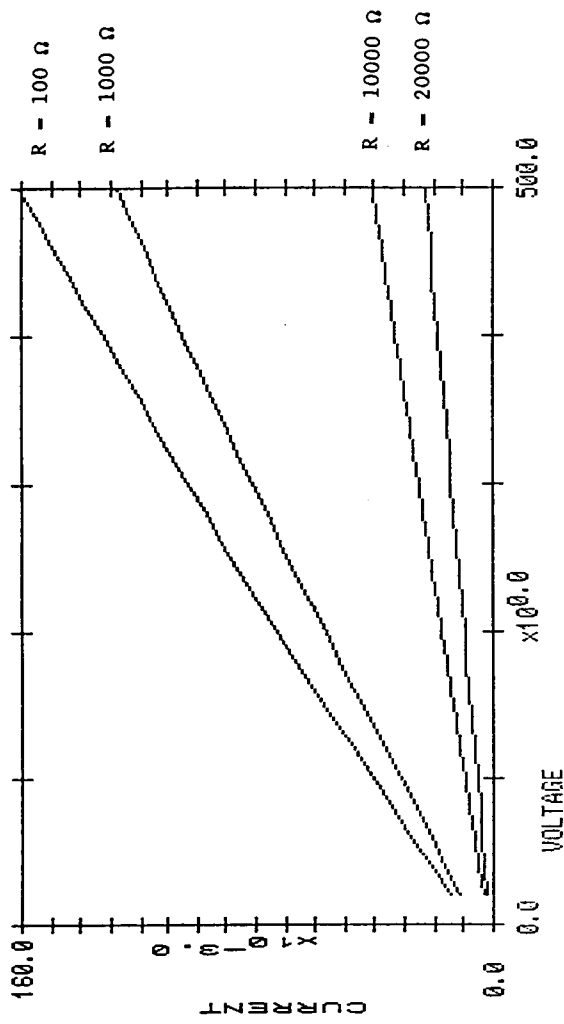
In addition, both the use of thermionic emitters and hollow cathode devices was considered. The non-linear relationships for these two devices are given. The relationships for the passive collection models are also given.

To illustrate the electrodynamic capabilities of the GATE, next 4 pages show the results of a digital simulation of the tether-plasma circuit in the Alfven generator configuration while the fifth page shows the results for the Alfven motor configuration. Passive electron collection is assumed at the anode, or mother subsatellite, and active thermionic emission is assumed at the daughter subsatellite, the cathode of the system. For simplicity, the anode is assumed to be a metallic sphere. The tether resistance is fixed at 100Ω and the total circuit ohmic resistance at 1000Ω . In each case, an ion density of $2 \times 10^{11}/\text{m}^3$ has been assumed, although densities up to $20 \times 10^{11}/\text{meter}^3$ have been recorded¹³⁻¹⁸.

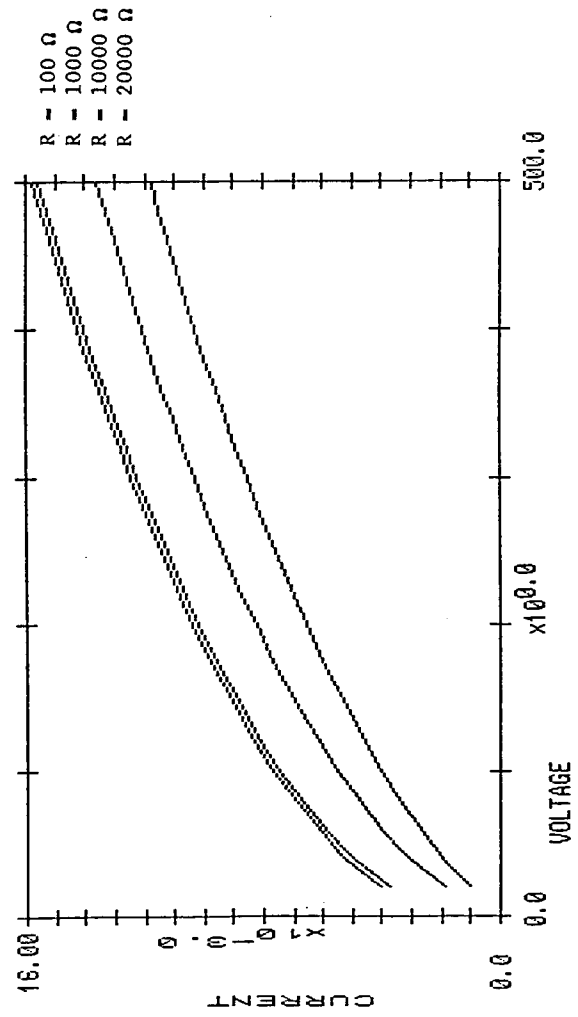
DOBROWOLNY-JANVE MODEL WITH THERMIONIC EMITTER



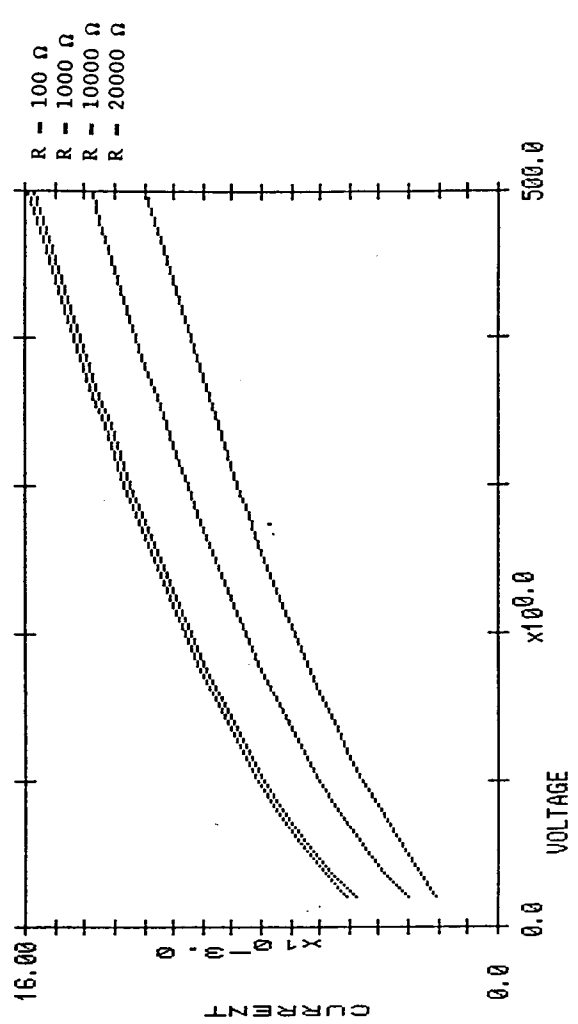
DOBROWOLNY-JANVE MODEL WITH HOLLOW CATHODE



PARKER-MURPHY MODEL WITH THERMIONIC EMITTER



PARKER-MURPHY MODEL WITH HOLLOW CATHODE

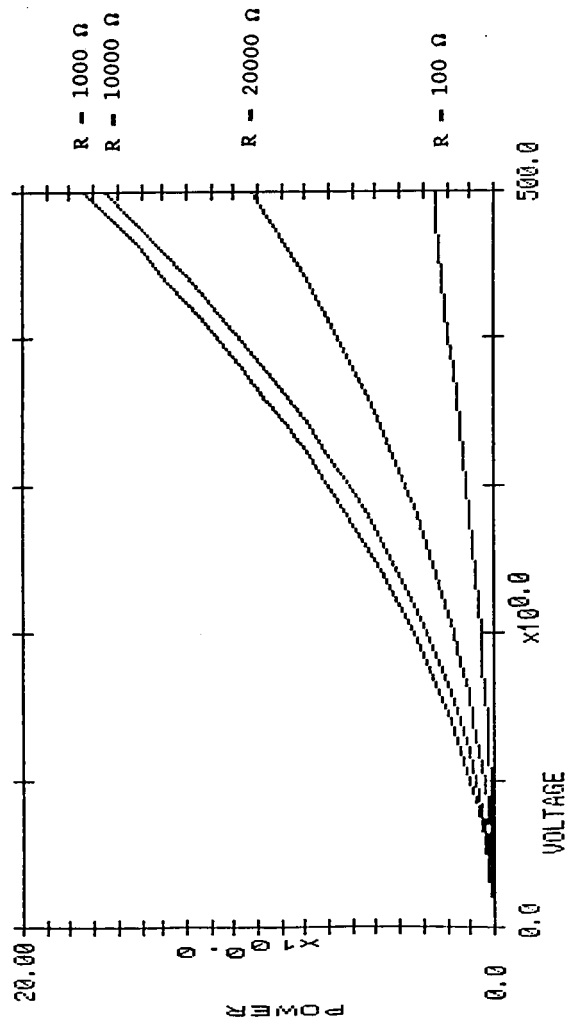


It is interesting to compare the simulation results using a hollow cathode model versus a thermionic emitter model. This is done in the figures on the following three pages. With the same electron collection model, there are virtually no differences in the current voltage relationships for the GATE, the power - voltage relationships, or the power - resistance relationships. The only notable difference occurs for resistance of less than $100\ \Omega$ with the Dobrowolny-Janve collection model. These data imply that the current in the GATE is strictly limited by the passive collection of electrons by the mother satellite.

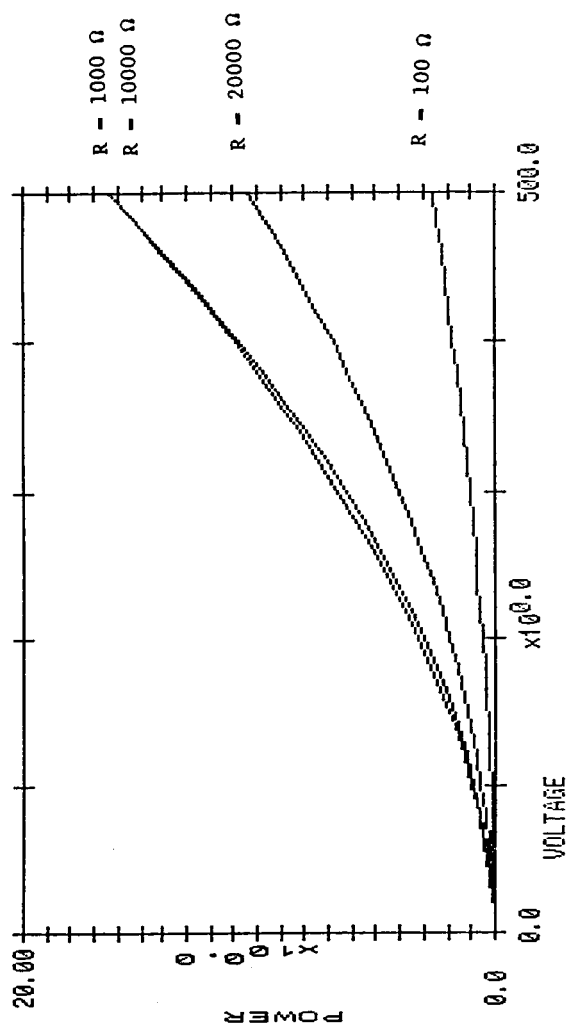
All of the accompanying figures are plots of tether current versus induced voltage. (a) uses the Dobrowolny-Janve model with a thermionic emitter while (c) uses the same model with a hollow cathode. (b) uses the Parker-Murphy model with a thermionic emitter while (d) uses the hollow cathode device. It is interesting to note that when the same collection models are compared (a-c or b-d), the results are virtually identical with both a thermionic emitter or a hollow cathode device. The only differences occur with small values of total circuit resistance ($R \leq 100\Omega$) with the hollow cathode device. Using a thermionic emitter, no differences occur. These results indicate that GATE is current limited strictly by electron collection.

Comparing between particle collection models (comparing a with b and c with d), significant differences are encountered. The Dobrowolny- Janve model results in an increase of almost an order of magnitude more current flowing in the tether. These results occur with either electron emission device.

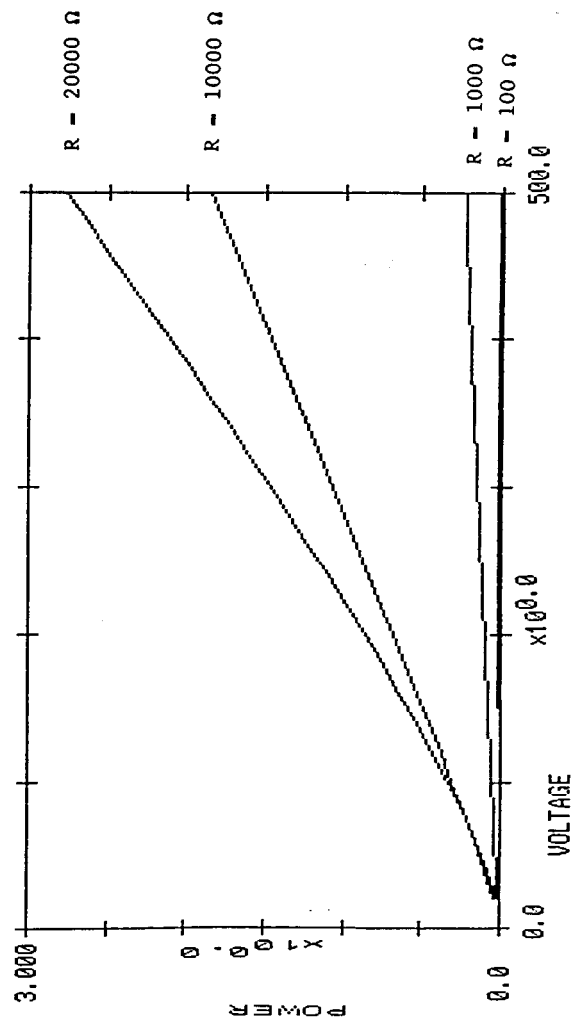
DOBROWOLNY-JANVE MODEL WITH THERMIONIC EMITTER



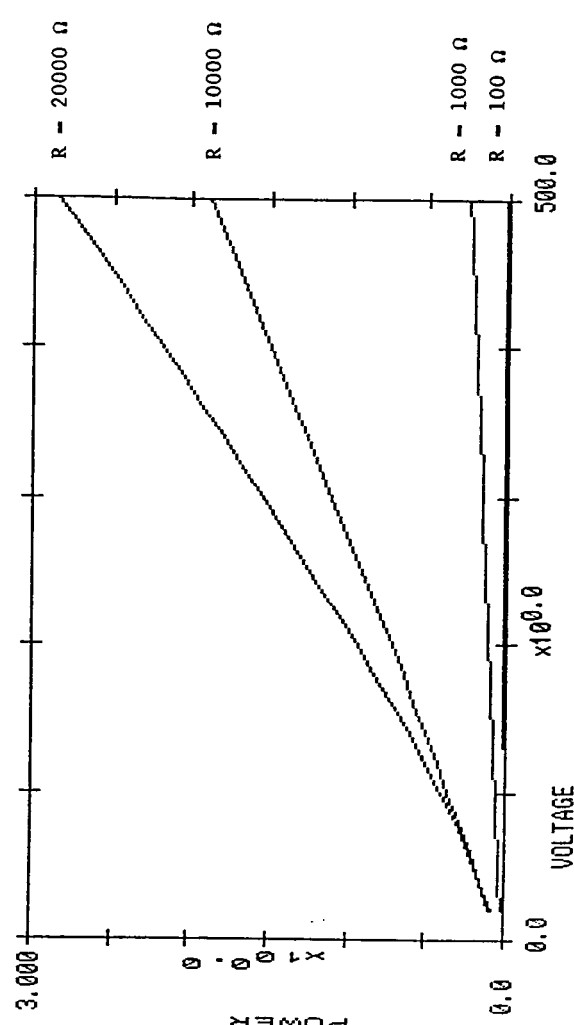
DOBROWOLNY-JANVE MODEL WITH HOLLOW CATHODE



PARKER-MURPHY MODEL WITH THERMIONIC EMITTER

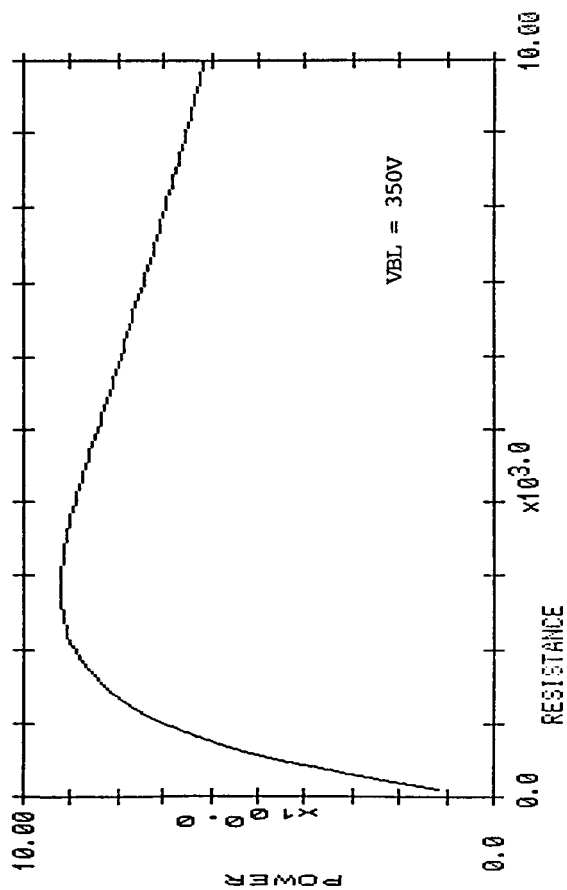


PARKER-MURPHY MODEL WITH HOLLOW CATHODE

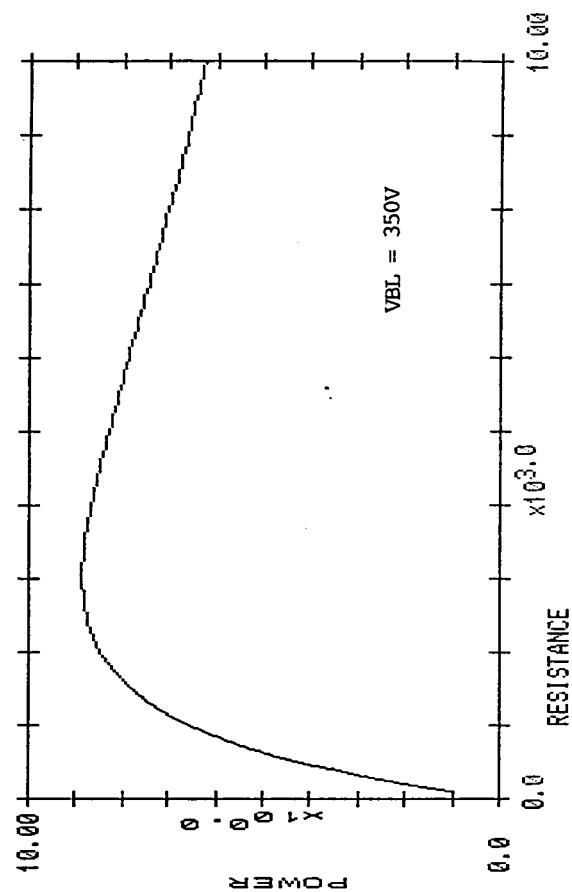


The accompanying figures all show the power converted from the tether current to batteries as a function of total induced voltage. Once again, figures a and c compare the thermionic emitter with the hollow cathode for the Dobrowolny-Janve model while figures b and d do the same for the Parker-Murphy model. Figures a and b compare the power converted with a thermionic emitter for the two particle collection models. Figures c and d perform the comparison for the hollow cathode device. Two observations can be made: Virtually no differences occur as a result of the electron emission process; and, the Dobrowolny-Janve model results in a prediction of about five times the converted power.

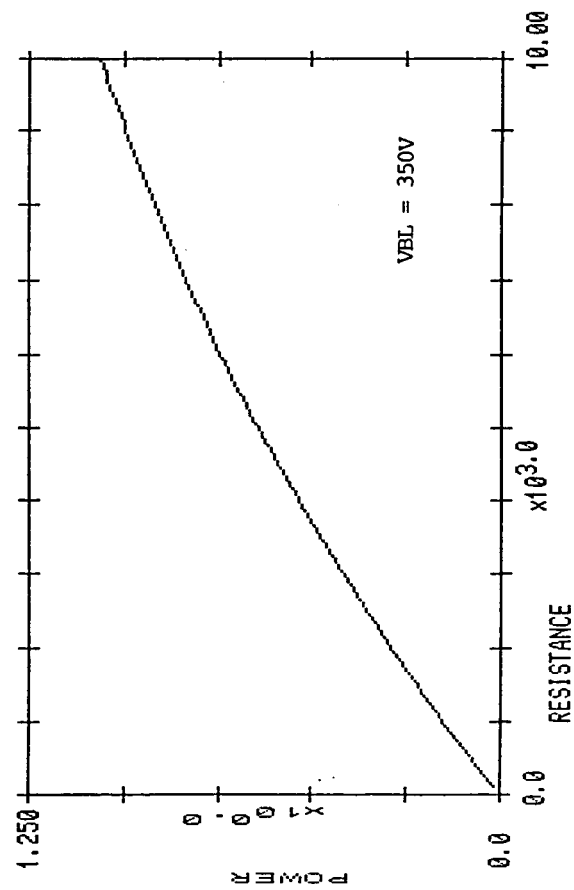
DOBROWOLNY-JANVE MODEL WITH THERMIONIC EMITTER



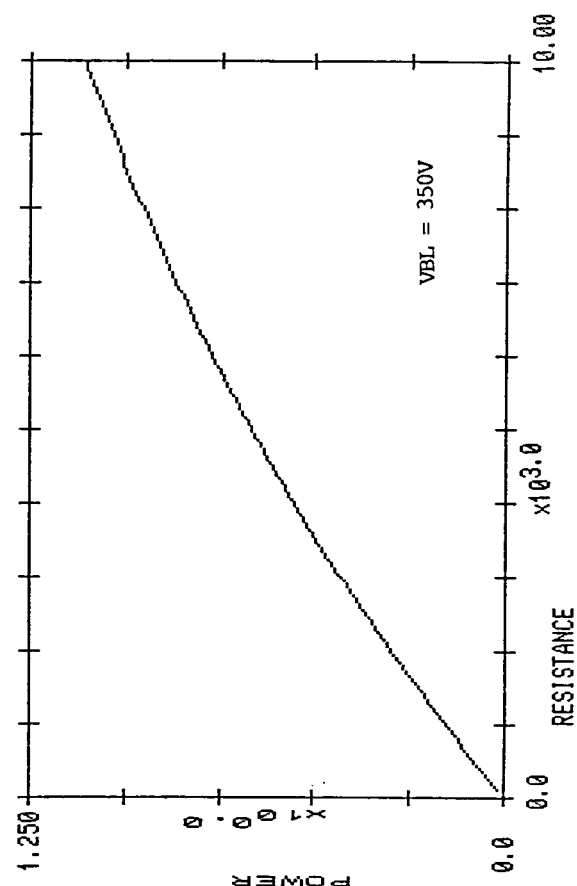
DOBROWOLNY-JANVE MODEL WITH HOLLOW CATHODE



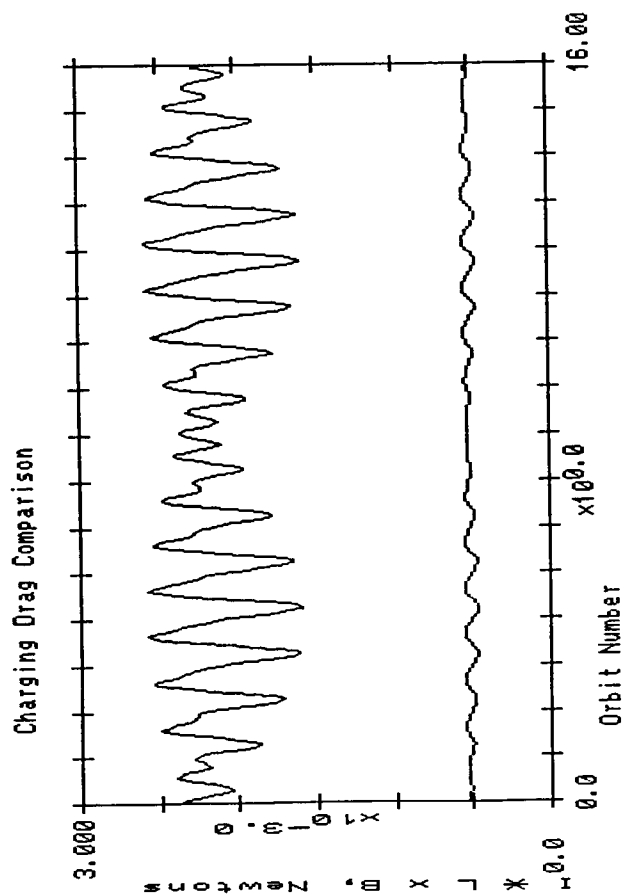
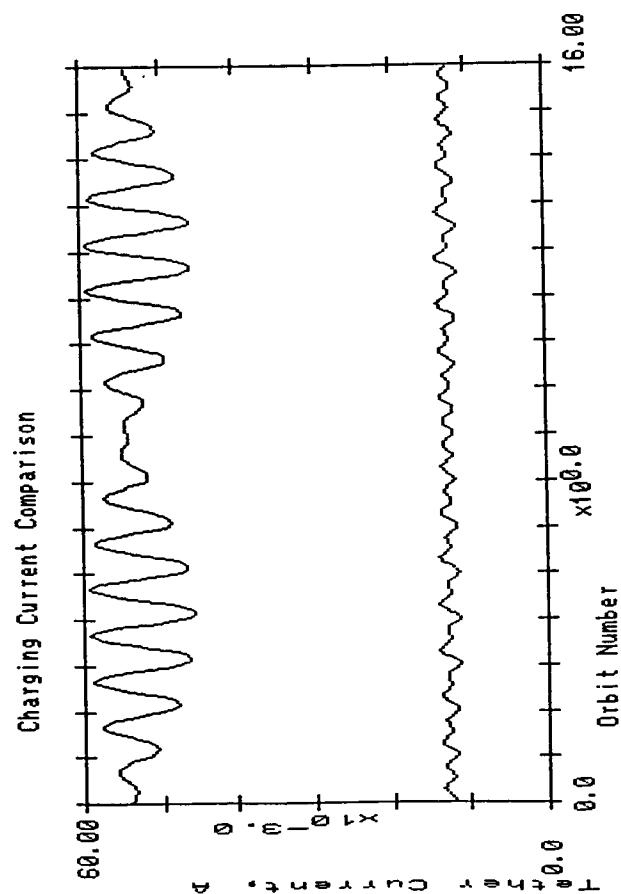
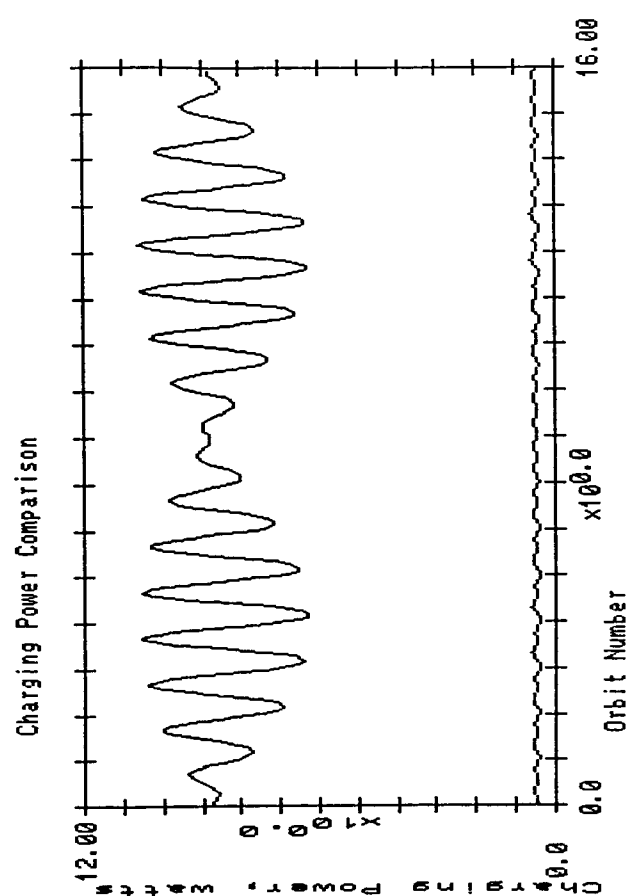
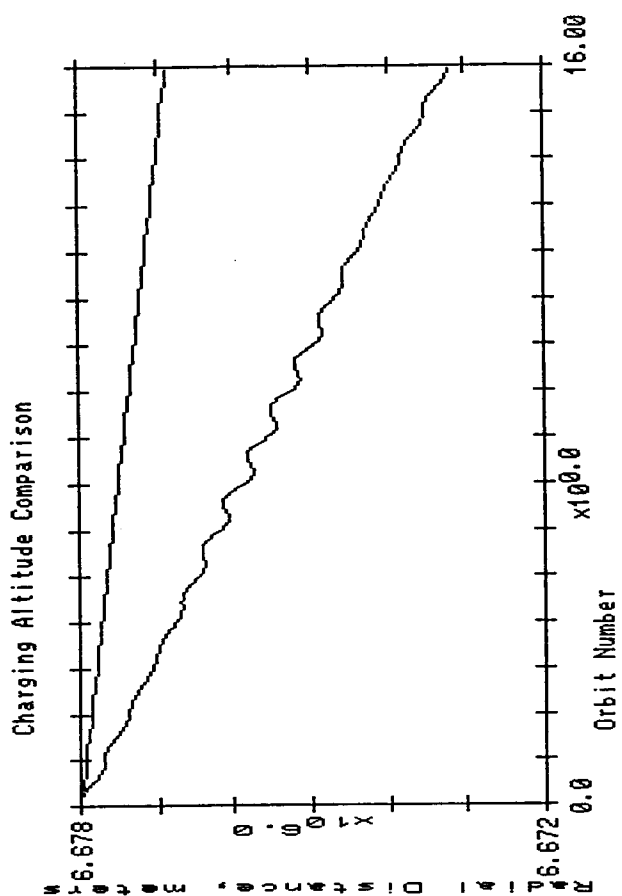
PARKER-MURPHY MODEL WITH THERMIONIC EMITTER



PARKER-MURPHY MODEL WITH HOLLOW CATHODE

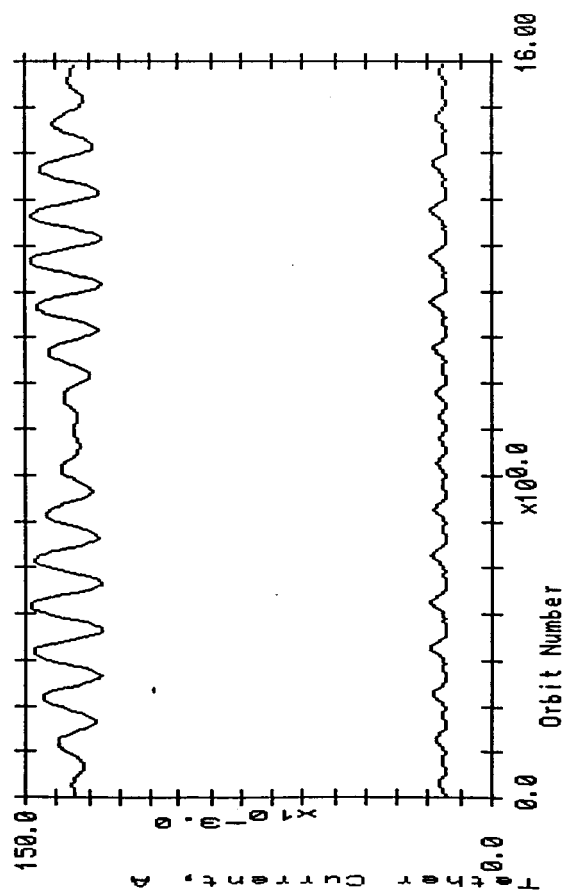


A comparison of the power converted as a function of total circuit resistance is given. Figures a and c compare the two types of electron emission devices with the DJ model while b and d compare makes the comparison for the PM model. All plots are done using a VBL of 350V. With the PM model, no maximum power level is achieved up to 10,000 Ω . With the DJ model a maximum power conversion is achieved between 2000 - 3000 Ω .

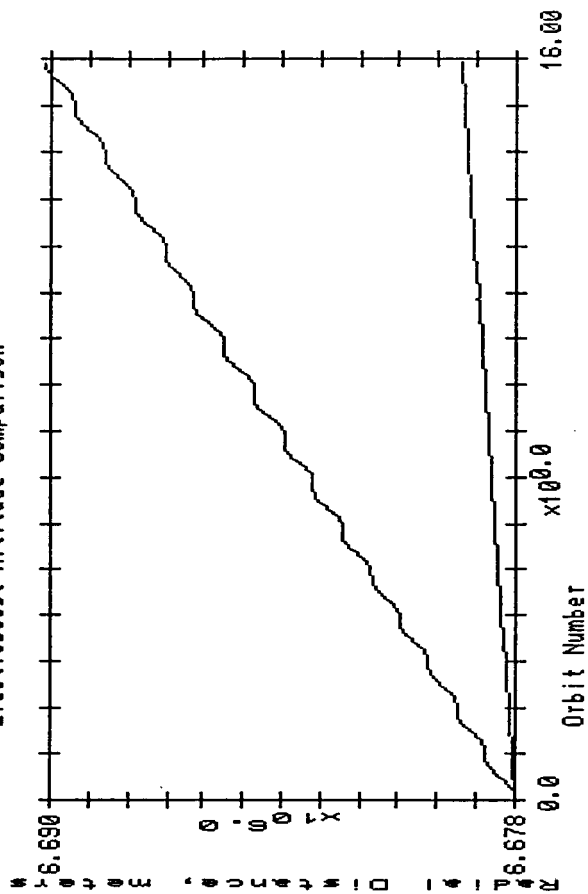


The tether current, electro-drag force, orbit degradation, and power generated are given versus orbit number. The EMF source for this simulation is the induced VBL of page 11. In each figure, the results are shown using both the Parker-Murphy (PM) model and the Dobrowolny-Janve (DJ) collection models. The method used for electron emission was thermionic emitters. For the DJ model the charging current averaged 53ma; the drag force averaged 2.25mN; and, the power generated averaged 9W. For the DJ model the altitude was reduced approximately 5km per day. The results using the PM model were approximately an order of magnitude less than those obtained from the DJ model. Variations of the colatitude of the system with geomagnetic north caused the currents, forces and power to vary by about 15%.

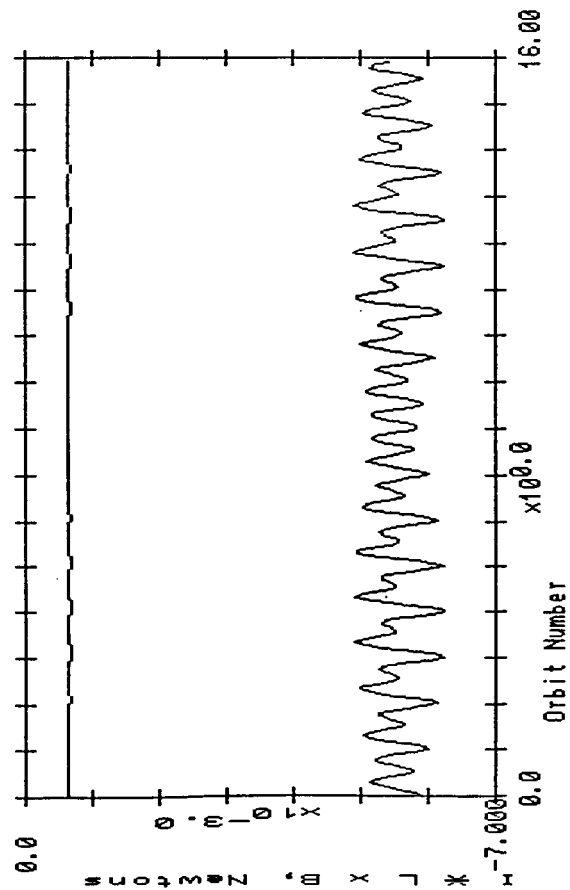
Electroboost Current Comparison



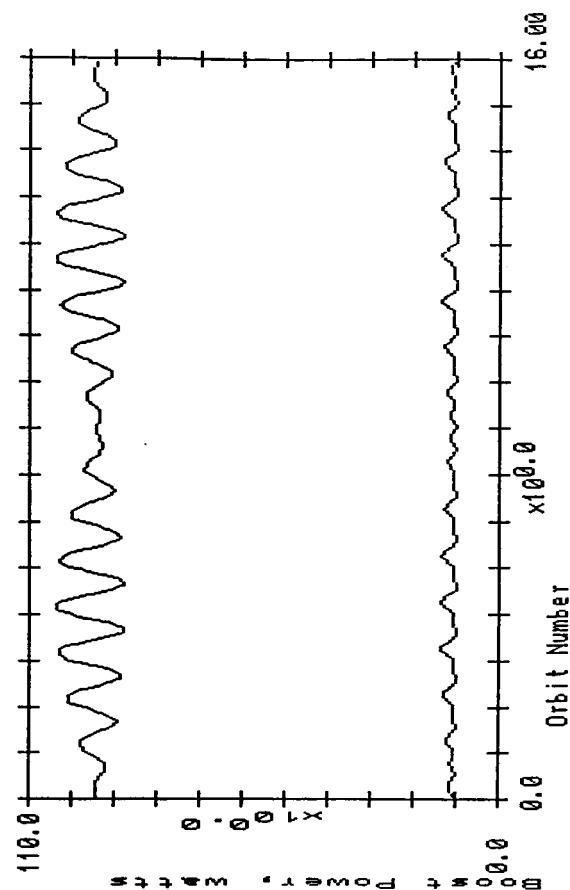
Electroboost Altitude Comparison



Electroboost Thrust Comparison



Electroboost Power Comparison



These figures show the tether current, electro-boost force, power supplied by the batteries and orbit increment versus orbit number. The EMF source for this simulation was 700V supplied by a DC to DC converter less the induced VBL of page 18. The satellites were 'flipped' for this simulation so that current would flow down the tether. The total series resistance was 200Ω (100 in the tether and 100Ω DC-DC convertor output resistance). Once again, the performance was bracketed by use of the two collection models and thermionic emitters were considered. The current averaged 135ma using the Dobrowolny model; the thrust averaged 5.5mN; the orbit was boosted by 12km per day; and, an average power of 95W was expended. Using the Parker- Murphy model these results were reduced by an order of magnitude. The currents, forces and power were not constant due to the variations of the colatitude of the GATE with respect to geomagnetic north.

ELECTRODYNAMIC CONCLUSIONS

----- TETHER CURRENTS 10X USING
DOBROWOLNY MODEL

----- P_{MAX} AT $3K\Omega$ FOR DOBROWOLNY
MODEL ($V_{BL} = 350V$)

----- 6.25W TO LOAD FEASIBLE

----- NO FUNCTIONAL DIFFERENCES
BETWEEN THERMIONIC EMITTER
AND HOLLOW CATHODE OVER
GATE RANGE OF INTEREST

In summary, the tether currents are approximately an order of magnitude greater using the Dobrowolny-Janve model over the Parker-Murphy model. With the DJ model the power converted to storage is maximized at a load resistance of $3k\Omega$ while using the PM model a maximum was not observed. In addition, 9W to the load appears to be feasible in a charging cycle. The most surprising result was that no function differences occurred between thermionic emitters and hollow cathode devices.

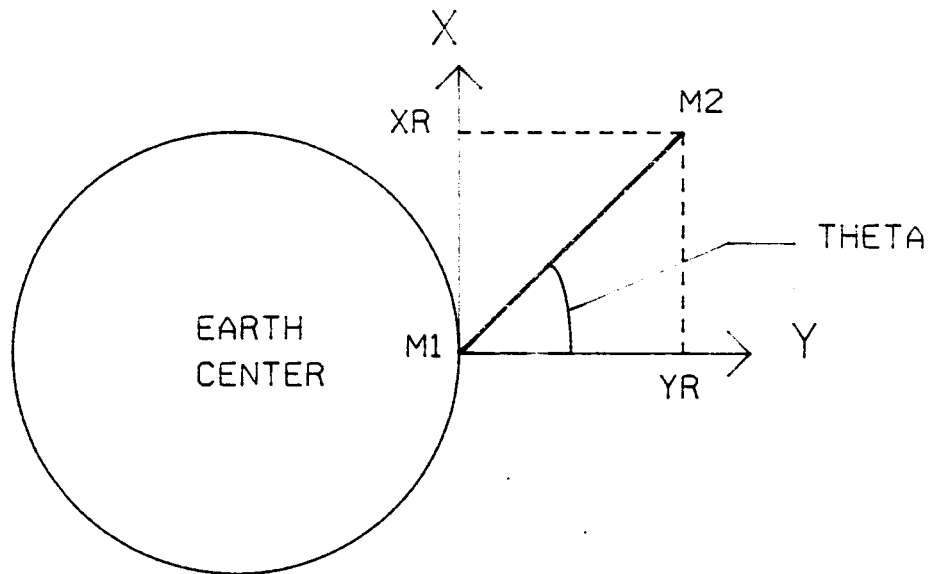
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DEPLOYMENT AND ATTITUDE CONTROL

- COORDINATE SYSTEM
- SEPARATION AND STABILIZATION ALONG LOCAL VERTICAL
- ORIENTATION (ATTITUDE) REVERSAL

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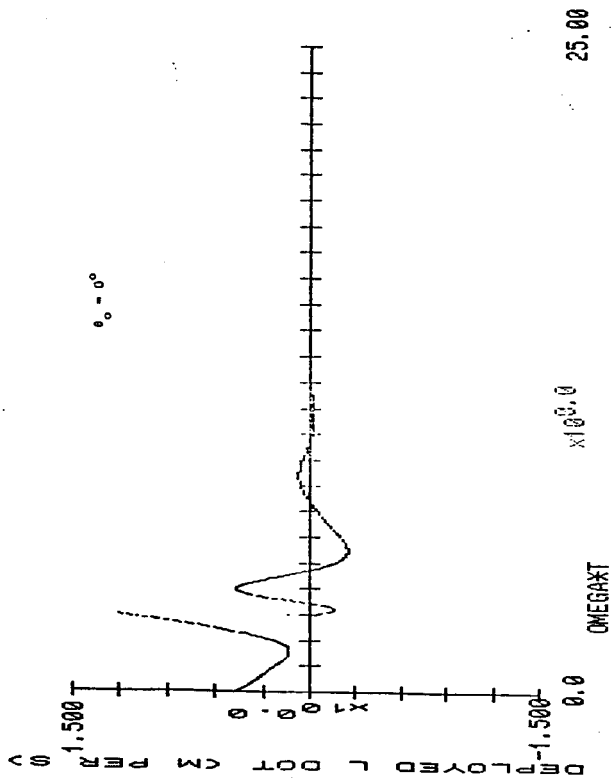
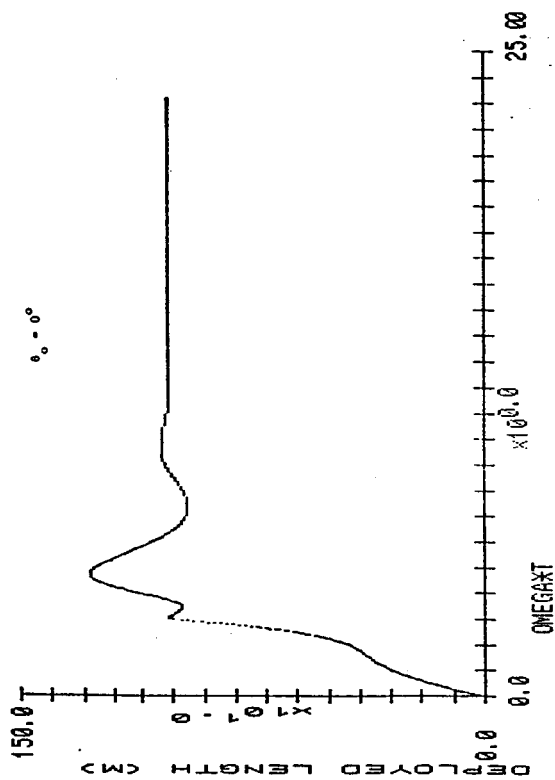
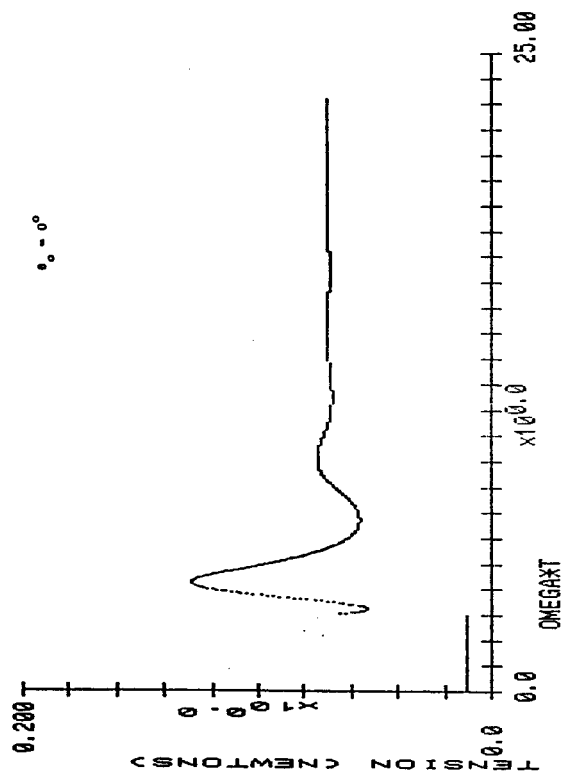
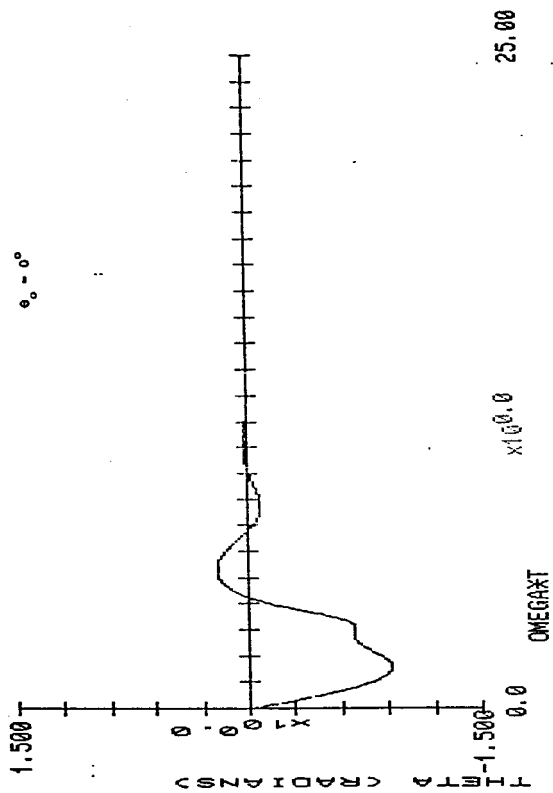
ORBIT PLANE



DEPLOYMENT AND ATTITUDE CONTROL

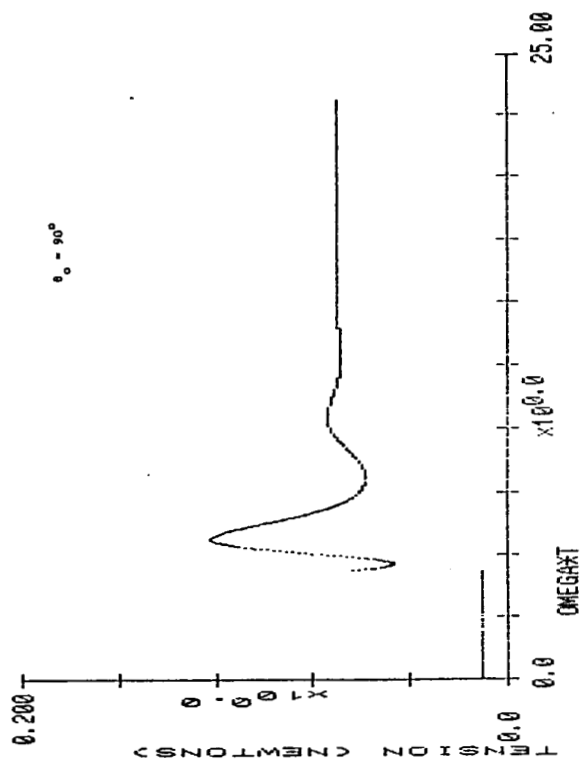
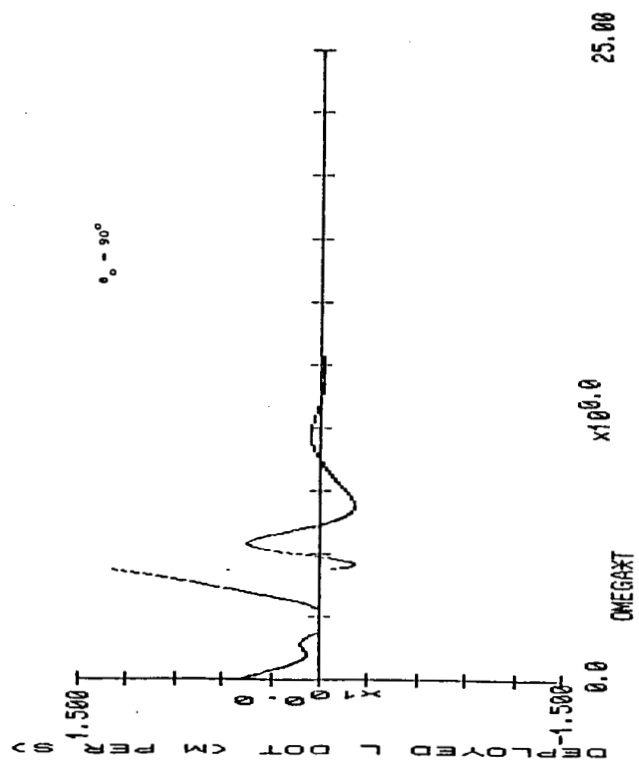
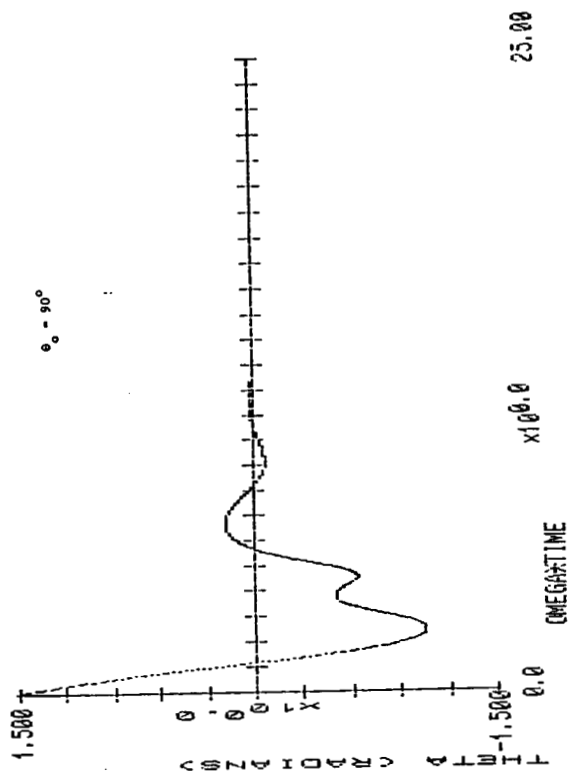
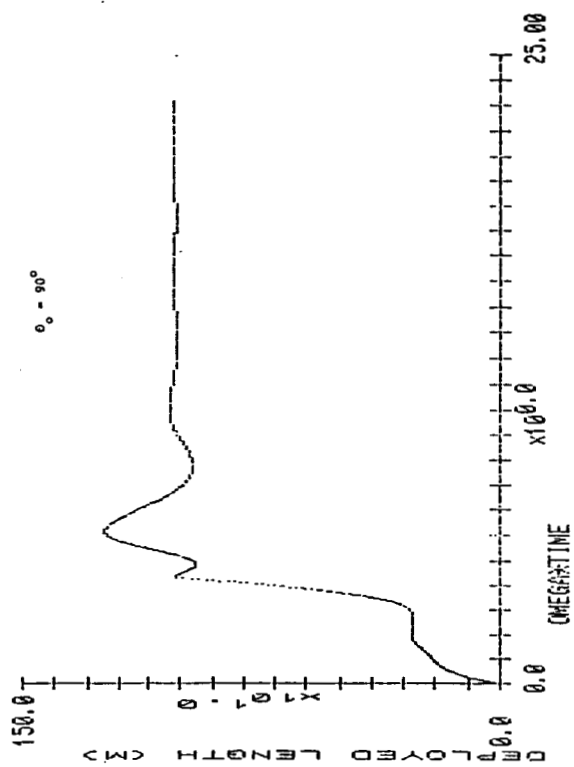
A dynamic model of the GATE system was developed and implemented to allow deployment and attitude control simulations. Out-of-plane motion was not implemented due to the preliminary nature of this work. The planar coordinate system used in the simulation is given in the opposite figure. The X-axis is defined to be tangential to the orbit plane, while the Y-axis is directed away from the Earth's center. The origin is located at M1. M1 and M2 represent the masses of the two subsatellites. All planar motion is defined relative to mass M1. The angle theta is a measure of M2 relative to local vertical. L and \dot{L} are the deployed length and length rate.

When the satellite system is ejected from the GAS can the mother-daughter subsatellites are connected by a locking mechanism. This locking mechanism is released and the springs give an initial separation velocity between the mother-daughter pair. As separation continues the the gravity gradient forces and the differential centrifugal forces cause the separation to accelerate. Initially, the friction wheel deploys 300 m of tether. The second 700 m is deployed by the motor driven reel in the mother. During this deployment phase, an active control system regulates the length, length rate, and necessary damping until the system is fully deployed (1 km) and stabilization is achieved.



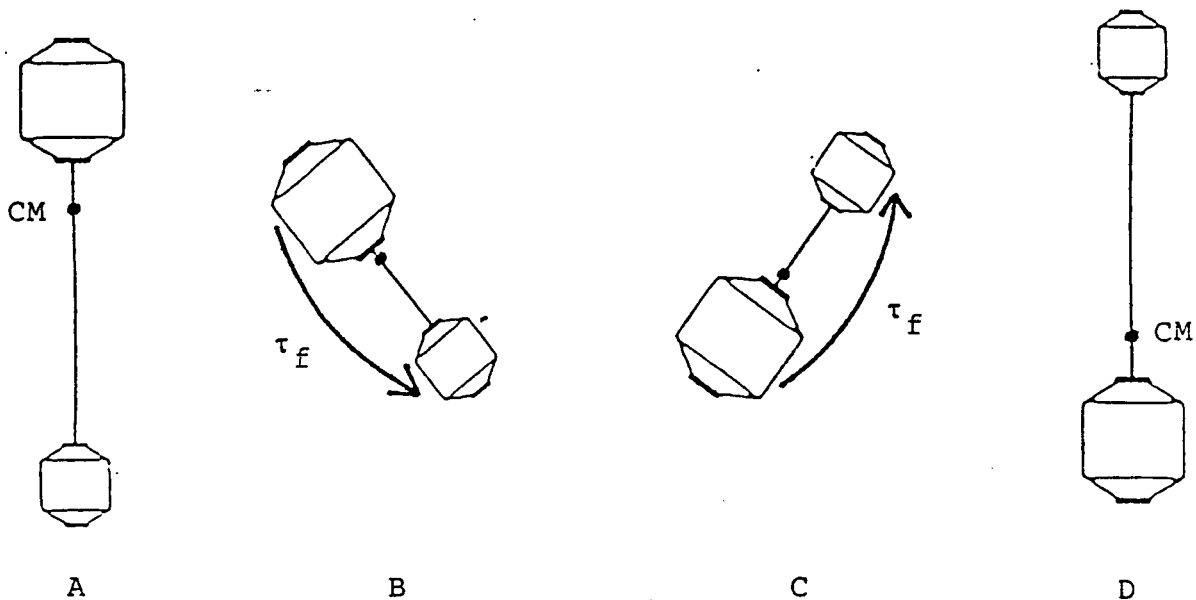
Since the GATE system has no thruster reaction control system, explicit control over translation and rotation is limited. Therefore a more subtle approach is necessary. A control law was developed by Rupp⁵ that only requires the amount of tether deployed, the rate of tether deployment, and the commanded length. This control law assumes one of the subsatellites is much more massive than the other. Although this is not the case in the GATE system, this presents only minor modifications in the control algorithm.

The opposite figures (a-d) show a typical deployment sequence using the control laws mentioned where the satellites are initially aligned along local vertical ($\theta_0 = 0^\circ$). Figure (a) shows deployed length, L ; (b) shows length rate; (c) shows angle from local vertical, θ and, (d) shows tension in the tether. As the deployed length exceeds the commanded length, the tension in the tether increases to return the deployed tether to 1km. The in-plane angle from local vertical swings from 0° as the tether deploys to about -45° and settles out to local vertical. The complete deployment and settling requires less than 2.5 orbits.



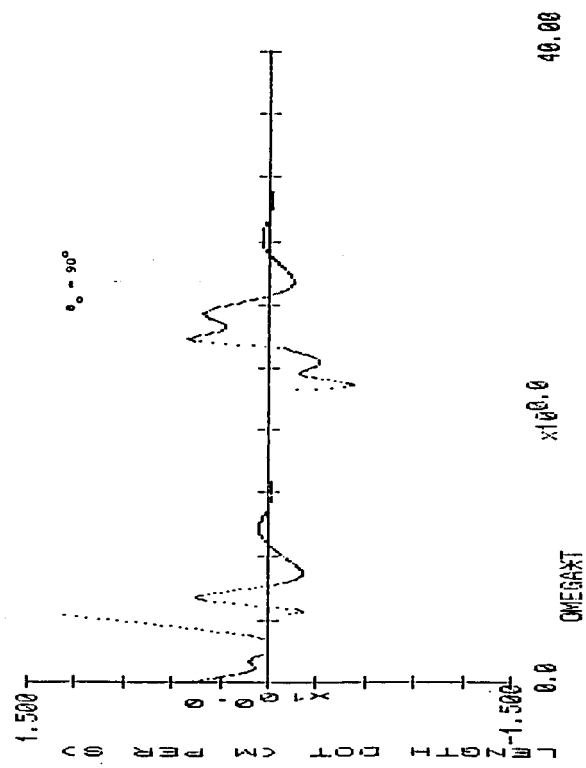
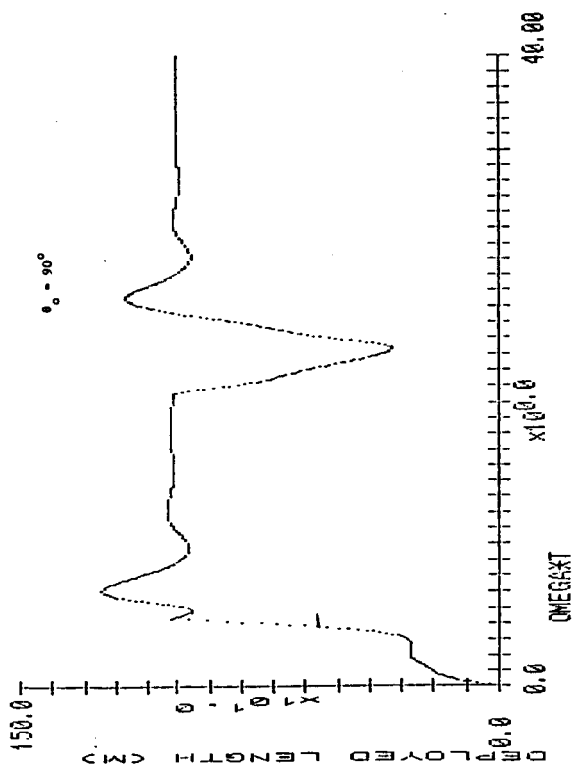
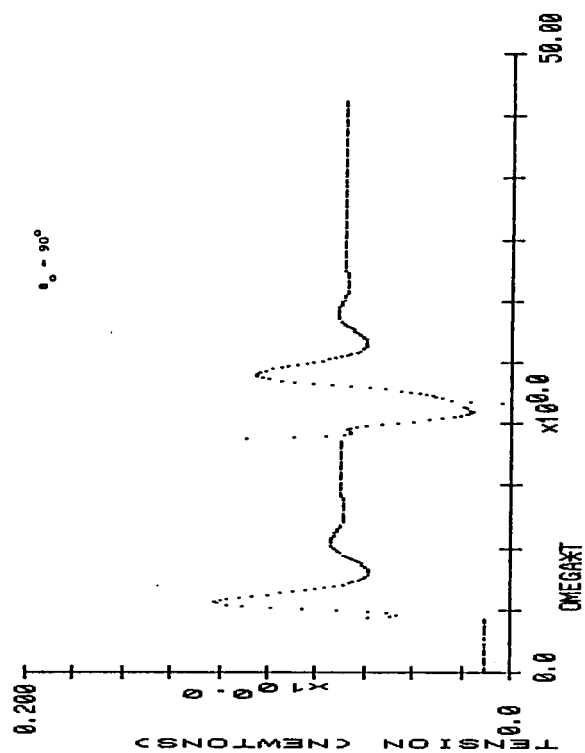
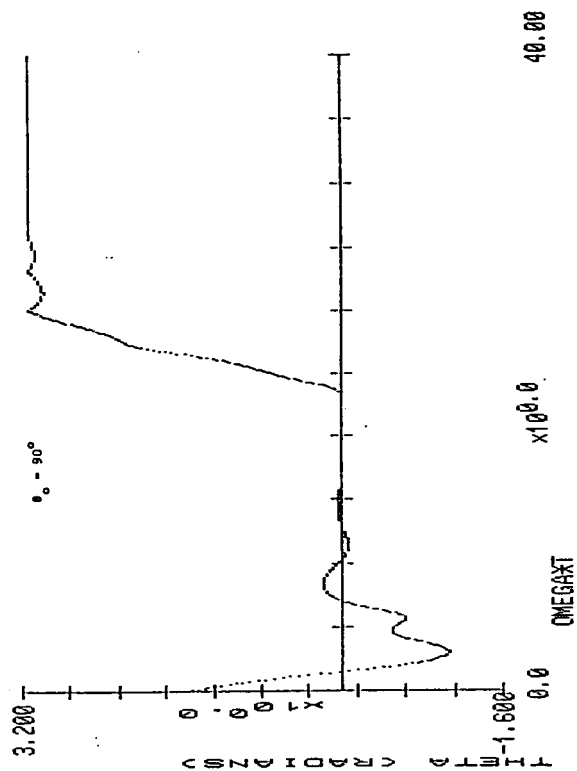
The opposite figures (a-d) show a typical deployment sequence where the satellites are initially aligned along local horizontal ($\theta_0 = 90^\circ$). This represents the worst-case in-plane angle from which deployment is initiated. Figure (a) shows deployed length, L ; (b) shows length rate; (c) shows the angle θ from local vertical; and, (d) shows tension in the tether. As in the previous deployment case ($\theta_0 = 0^\circ$), the tension control law stabilizes the system to a full length of 1 km. The in-plane angle starts from 90° , and as the tether deploys, swings to a maximum of -60° before settling out to local vertical. The complete deployment and settling requires less than 2.5 orbits.

GATE Orientations



- A. GATE system in "charging" orientation
- B. Tether is partially reeled in giving a change in the system inertia which causes a torque τ_f about the CM
- C. Torque τ_f is used to fully re-deploy the system
- D. GATE system in "electro-boost" orientation

As a strictly collection satellite-emission satellite configuration is envisioned, there are two attitudes needed along local vertical. Therefore a method for reversing the orientation of the system is necessary. This "flip" maneuver about the system's CM may be accomplished using the same control law as was used in initial deployment. When the decision is made to reverse the orientation of the system, the controller will begin tether retrieval. The change in moment of inertia causes the spin rate to increase from the normal orbital rate to about twice orbital rate. This maneuver is depicted in the figure. In preliminary dynamic simulations the retrieval length was 300 meters which produced enough angular rate to spin the system past local horizontal. Once the system rotated beyond local horizontal the control system began re-deploying until stabilization along local vertical was again achieved. Simulation has shown that this control method is feasible in accomplishing the orientation maneuvers.



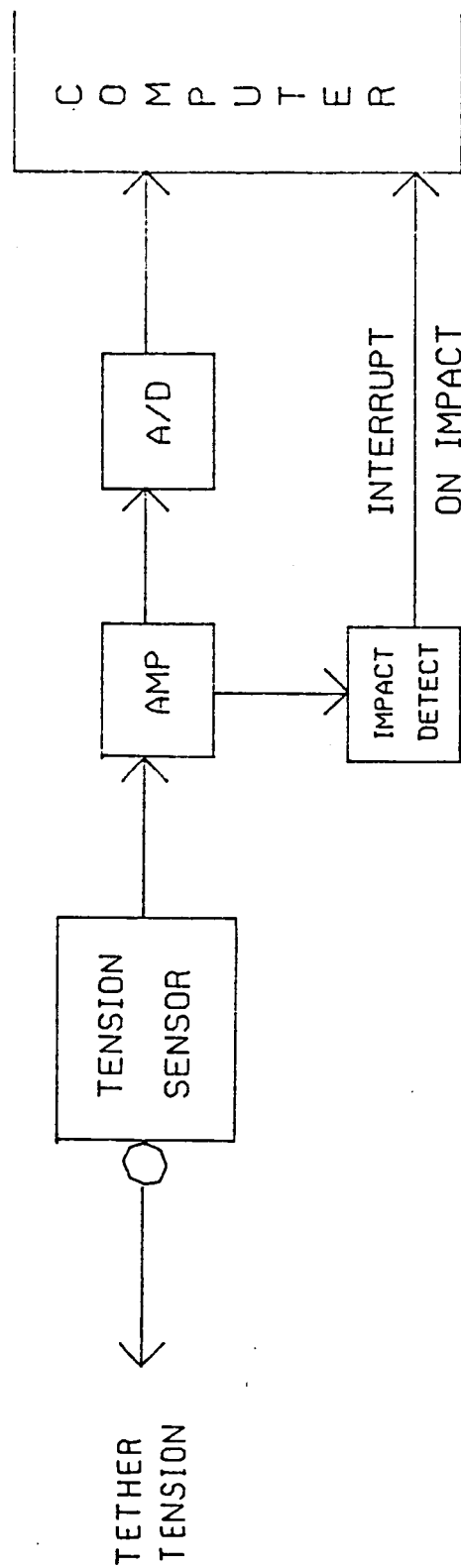
Figures (a-d) show a 'flip' maneuver. As in previous figures, (a) shows deployed length; (b) shows length rate; (c) shows angle from local vertical; and, (d) shows tether tension. After initial deployment and stabilization, the tether is rapidly reeled in to a length of 300m causing the system to go unstable and the in-plane angle, θ , to rapidly change. Once the system crosses local horizontal, the control law again initiates the deployment sequence. The tether tension is once again modulated using the length and length rate control laws, whereby, oscillations in in-plane angle and length are rapidly damped. θ changes from 0° to 180° within approximately one-half orbit.

CONCLUSION

- DEPLOYMENT AND STABILIZATION OCCUR WITHIN 2.5 ORBITS
- ORIENTATION REVERSAL AND STABILIZATION REQUIRE 2.5 ORBITS AND AN ENERGY REQUIREMENT OF APPROXIMATELY 30 JOULES
- CONTROL ALGORITHMS PROVED ADEQUATE IN PRELIMINARY ANALYSES

As seen in the previous figures of deployment and attitude control, impulsive type tension spikes occur during deployment when the commanded length is initially achieved. Although the tension spike is only on the order of 1 Newton for GATE, it could excite tether modal vibrations and librations. A smoother control strategy could minimize these effects. Ongoing work involves the study of uniform and exponential deployment rates such as those proposed by Misra and Modi^{6,7}. Control laws based on the application of Linear Quadratic Regulator theory using length, length rate, pitch and pitch rate are also being investigated⁸. In conclusion, the simulations show that deployment, stabilization, and attitude control is feasible for the GATE system. Future work includes development of a three dimensional dynamic simulation incorporating aerodynamics, electrodynamics, vibration effects, and alternate control strategies for deployment, station-keeping, and attitude control.

GATE TENSION/IMPACT MEASUREMENT SYSTEM



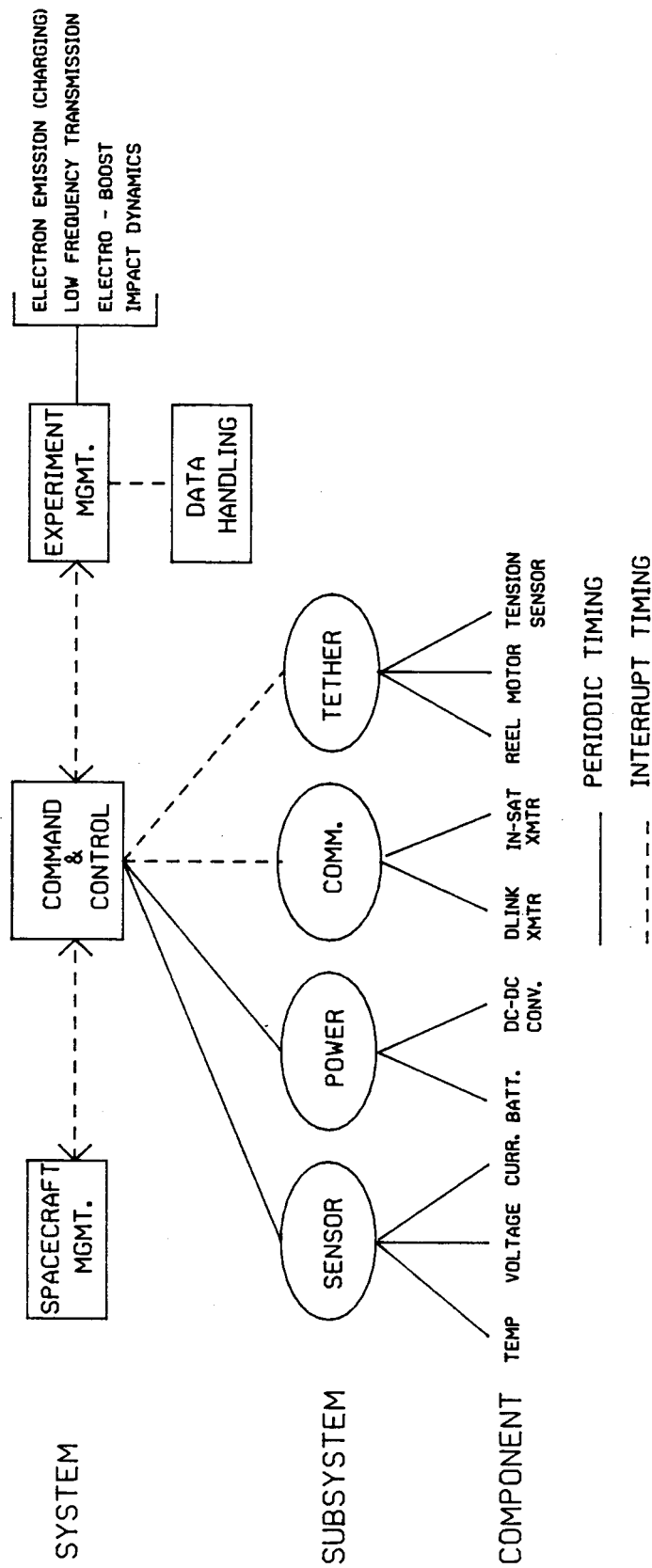
- PROVIDES TENSION FEEDBACK TO CONTROLLER
- PROVIDES MICROMETEOROID IMPACT SIGNAL FOR ANALYSIS
- IMPACT DETECTOR ALERTS DORMANT COMPUTER

GATE TENSION/IMPACT DYNAMICS

The GATE Tension/Impact Measurement System is shown in Figure 7. The system provides two signals; tension and impact alert. The tension signal is used in the feedback loops of the tether controller. The impact alert signal is used to alert the dormant computer that an impact has occurred and tension should be monitored for experiment analysis.

A number of sensors have been evaluated including piezoelectric, displacement transducers such as variable resistance/reactance transducers and strain gauge sensors. Semiconductor strain gauge sensors appear to be the best candidates for meeting the dual goals of the system. Environmental compensations, calibration, and motion errors are the areas requiring additional work.

COMMAND AND CONTROL SYSTEM (MOTHER)



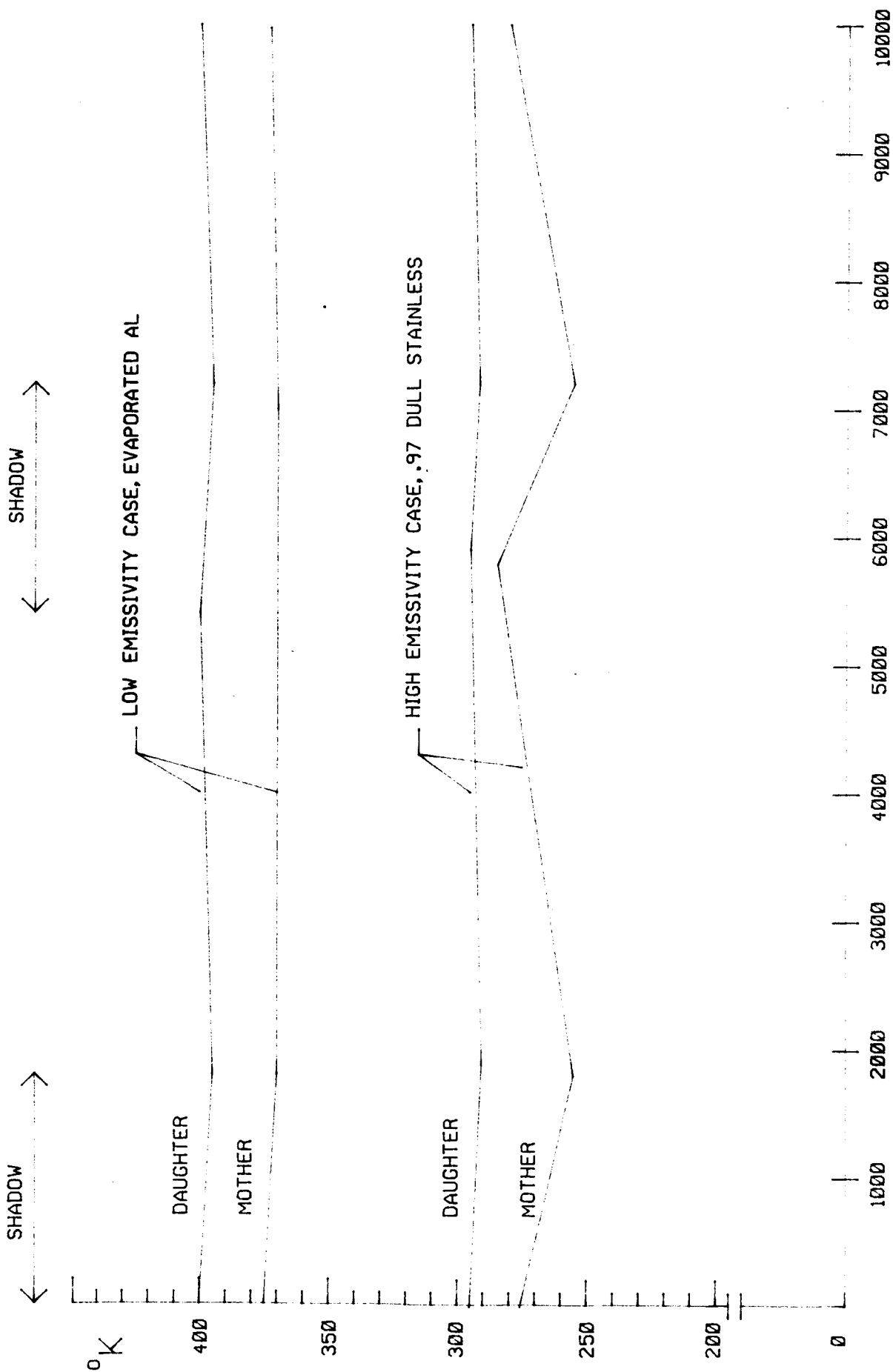
GATE COMMAND AND CONTROL SYSTEM

The command and control system is responsible for both spacecraft and experiment management. Performance, reliability, and resource optimization are key objectives. Pre-deployment status, deployment, station keeping, and experimentation are the primary tasks of the command system. The proposed subsystems are sensor, power, communication, and tether. Coordination and control of all subsystems will be provided by a central microprocessor. The microprocessor duty cycle will be divided between spacecraft operations such as attitude control as well as the scheduling, execution, and data handling of the experiments.

The command system will also be responsible for managing all aspects of experimentation. These include experiment scheduling, execution, and data handling. This will require knowledge of both system and environmental constraints. High data acquisition and handling rates are not anticipated because of the frequency characteristics of the experiments. Spacecraft management will include error checking, deployment, attitude control, and stationkeeping. Stationkeeping involves maintaining a local vertical orientation in the face of tether librations and disturbances.

Spacecraft and experimental activities are loosely synergetic: no experimentation will occur during spacecraft system operations such as initial deployment and orientation maneuvering. Once the system is aligned along local vertical (nominal or electroboost orientations), the primary efforts of the command system will be devoted to experimentation. Occasional stationkeeping maneuvers will be necessary to maintain the desired attitude. Because of the frequency of spacecraft system operations as well as low data rates, the total number of operations is well within the capabilities of a central low power microprocessor.

GATE THERMAL PROFILES



TIME (SECONDS)

THERMAL PROFILES

Two cases of the thermal properties for the GATE were studied: a low emissivity case and a high emissivity case. In each case the satellites were assumed to be spherical for ease of analysis with the mass properties given in the Physical Layout section. In the low emissivity case, The satellites were considered to be covered with evaporated aluminum. In the high emissivity case, the covering of the satellites was considered to be dull stainless. The accompanying figure shows the thermal histories for the two satellites over a two orbit period in the steady state. For the high emissivity case, the daughter maintains a temperature close to room temperature; the mother changes a total of about 30°C with an average of 265°C as it passes into and out of Earth's umbra. In the low emissivity case, both satellites heat up to over 350°.

Table 3

GATE POWER CONSUMPTION

<u>Subsystem</u>	<u>W-Hr/Day</u>
1. Electroboost 7w x 24 hr/day =	168.0
1 mission @ 15 day	
2520 w-hr/mission	
90 A-hr @ 28V	
2. Mother	
A. Computer & Electronics	6.5
B. Communications	3.5
C. Control	17.5
D. Other	10.0
TOTAL	37.5
90 day mission = 3375 w-hr	
120 A-hr @ 28V	
3. Daughter	
Sun Pointing	11.5
90 day mission = 1035 w-hr	
40 A-hr @ 28V	

GATE POWER

The projected GATE power consumption is given in Table 3. Three power systems are envisioned: 1. electroboost; 2. Mother; and, 3. Daughter. One or more of the systems will be recharged using the induced tether current allowing for reduced battery capacity. Total required power without recharge would be 210 A-Hr @ 28V for the mother. From space and weight consideration, 200 A-Hr @ 28V of silver-sinc batteries can be incorporated into the mother satellite. Additional storage of 40 A-hr can be achieved in the daughter.

TABLE 4

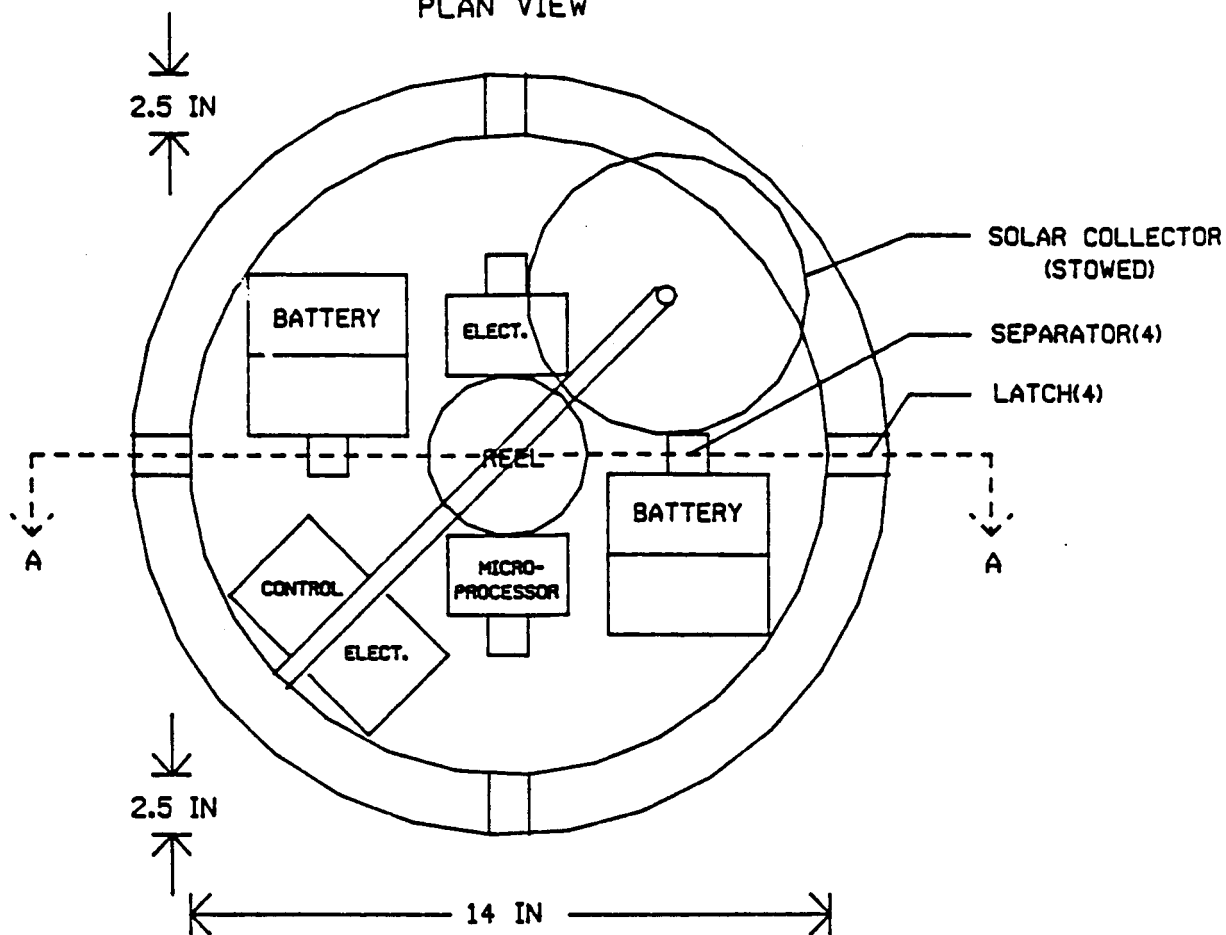
GATE POWER REQUIREMENTS WITH A 30 DAY
9W CHARGING CYCLE

<u>Subsystem</u>	<u>w/charging</u>	<u>w/o charging</u>
1. Electric Boost (2 missions: 15 days each)		
Required:	5040 W-Hr	5040
Supplied:	2240 W-Hr	0
<u>Net:</u>	<u>2800 W-Hr</u>	<u>5040</u>
28V @	100 A-Hr	180
2. Mother		
Required:	6750 W-Hr	6750
Supplied:	4240 W-Hr	0
<u>Net:</u>	<u>2510 W-Hr</u>	<u>6750</u>
28V @	90 A-Hr	210
3. Daughter		
Required:	2070 W-Hr	2070
Supplied:	605 W-Hr	0
<u>Net:</u>	<u>1465 W-Hr</u>	<u>2070</u>
28V @	52 A-Hr	74

The projected power requirements with a charging current of 30ma generating 9.0 W of usable energy for a 30 day charging period are given in Table 4. Under these apparently reasonable conditions, two electro-boost experiments could be accomplished with the available energy storage capacity by shifting a small fraction of the total stored energy from the mother to the daughter. After the second boost experiment, the satellites would be returned to the charging configuration for re-entry into the atmosphere.

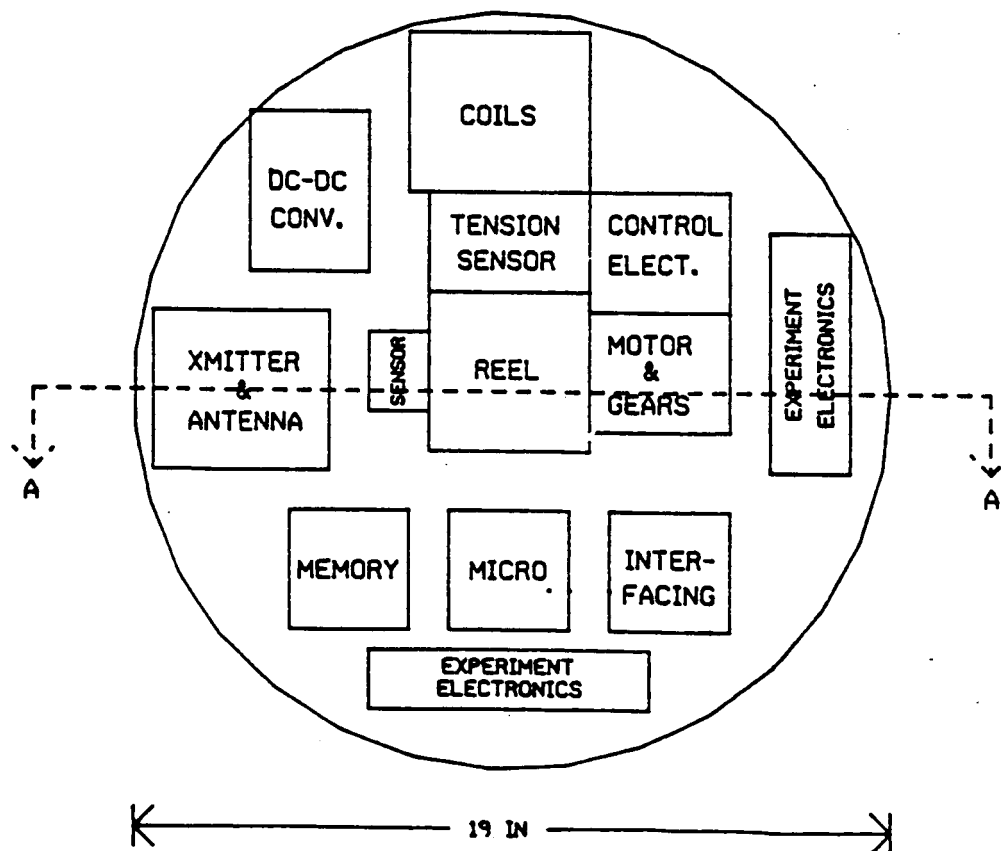
GATE SUBSATELLITE (DAUGHTER)

PLAN VIEW



GATE SUBSATELLITE (MOTHER)

PLAN VIEW



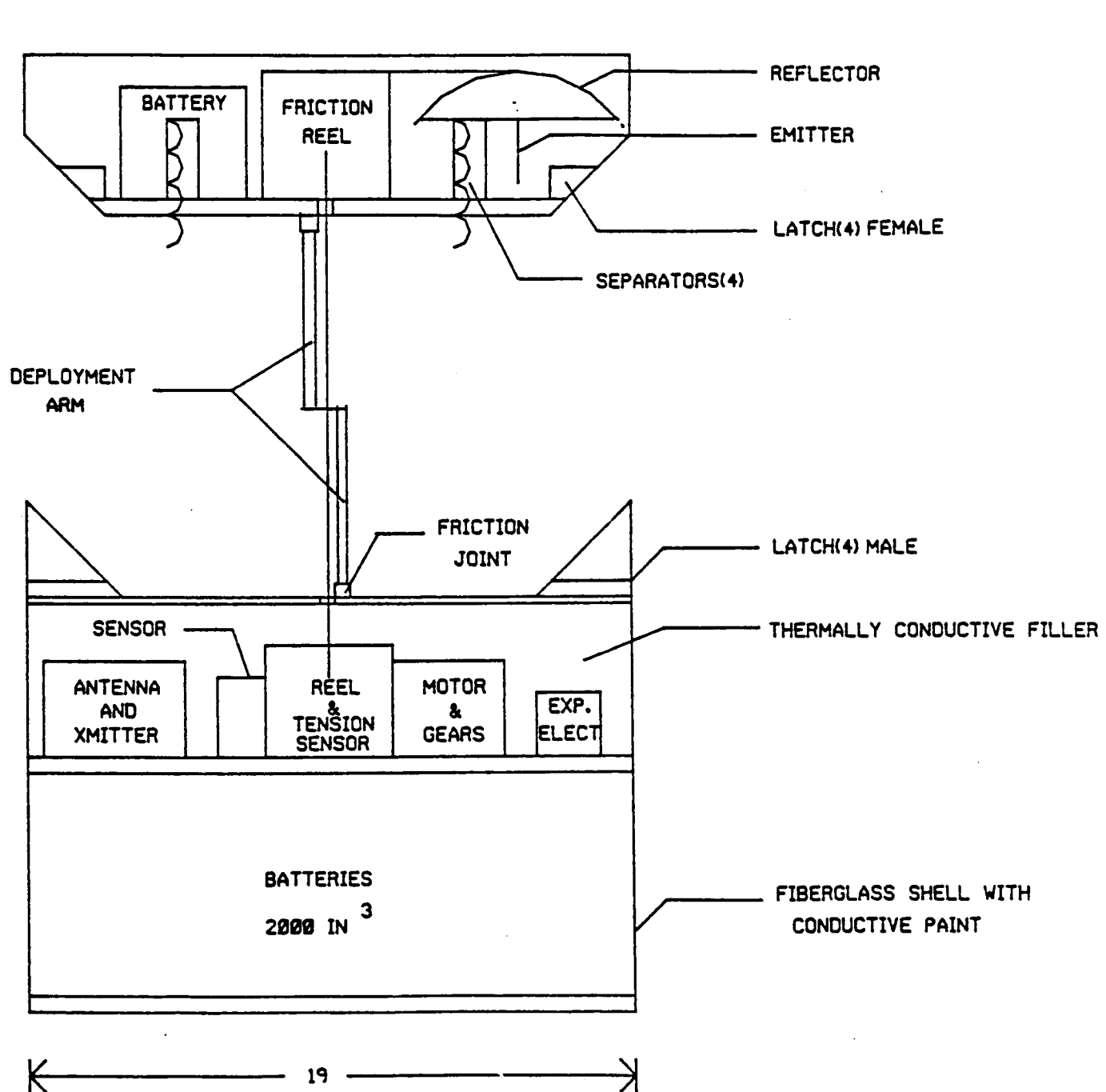
PHYSICAL LAYOUT

The first figure shows the plan view of both the mother and daughter satellites. A solar collector is shown in the daughter for the heating of a thermionic emitter. The control electronics and microprocessor are for the pointing of this collector. If plasma contactor is used, the daughter would contain only the plasma source and control, batteries, friction reel and separators. It is envisioned that about 300 m of tether will be deployed from the friction reel.

The mother satellite contains most of the batteries and virtually all control and experimental apparatus. It also contains a reel with 900 m of tether. This reel is actively controlled by a motor driven by the control laws. A tension meter is envisioned for motor linearization and an odometer for the tether control algorithms. A DC-DC converter is shown for recharging and electro-boost experiments and loading coils for LF propagation studies.

GATE SATELLITE SYSTEM

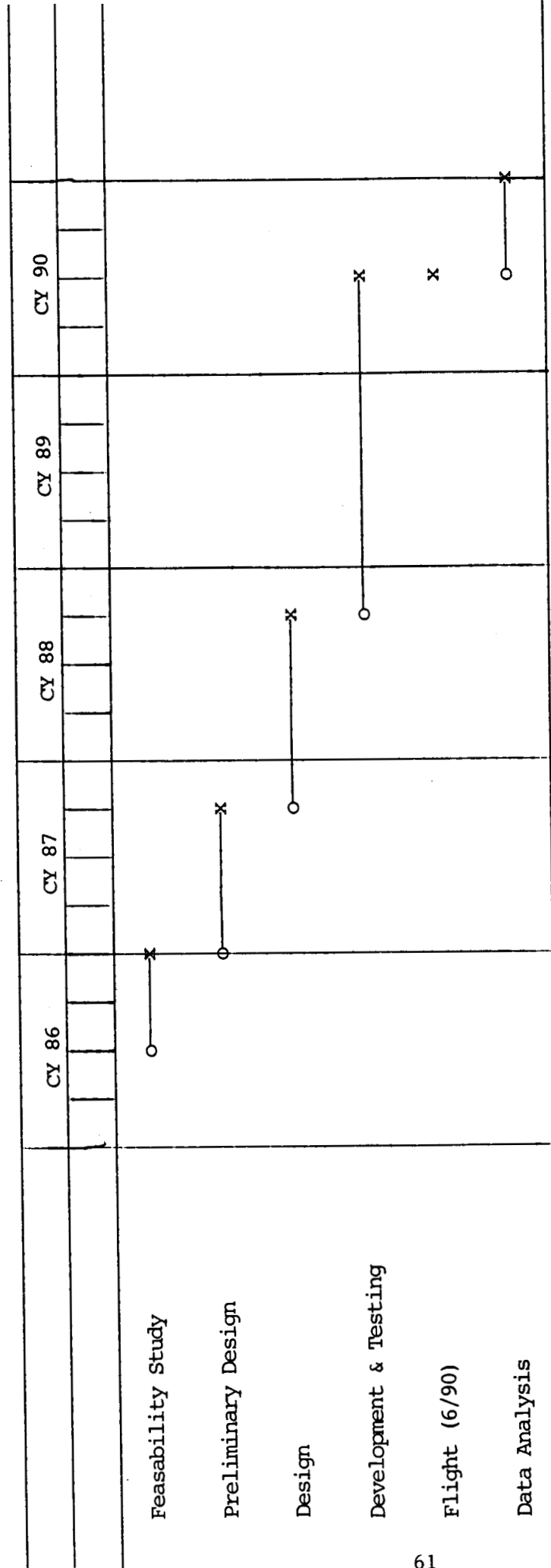
SECTION VIEW A-A



ALL DIMENSIONS IN INCHES

As seen in this figure, the mother is two layered with batteries on the bottom layer. This design keeps the C.M. of the system low relative to the GAS ejection plate. Approximate weights from the system are: mother, 120 lbs; daughter, 30 lbs. Prior to separation the deployment arms fold and the daughter nests into the top of the mother. Latches maintain integrity during launch and ejection from the GAS canister. Separation springs provide the initial velocity to deploy the satellites away from each other.

GATE Project Schedule



GATE RADAR CROSS SECTION

Measurement of the radar cross section of the long wire will require rendezvous of the orbiter with GATE at least one day after deployment. The orbiter should station keep at a range of 2 km to allow radar operations to begin. The measurements will consist of commanding the radar (with the orbiter in an appropriate attitude) to point to the approximate location of the center of the tether. The radar is then commanded to search while the signal strength (AGC) is monitored on telemetry. The search pattern is a spiral motion and will intersect the tether at various angles.

GATE PROJECT SCHEDULE

The GATE project schedule is shown in Figure 7. Preliminary design will start Jan 87 continuing through Sept 87. Design is projected to commence on Oct 87 lasting 1 year. Development and testing will last 18 months starting Oct 87. The flight will last approximately three months.

Possible PSN involvement would be in the areas of electrodynamics and controls. Specifically, PSN has expressed interest in studying plasma contactors, the charging and switching systems and the electroboost tradeoffs. Joint efforts will be conducted in the control and power systems. Final decisions relating to cooperative efforts will be made at appropriate levels.

CONCLUSIONS

- NO MAJOR TECHNOLOGICAL
STUMBLING BLOCKS
- FREE FLYER ADVANTAGES
- 60 DAY MISSION POSSIBLE
- DEMONSTRATE ELECTRO BOOST
AND ORBIT CHARGING
- RECORD METEOR IMPACTS
- DEMONSTRATE CONTROL STRATEGIES
- FAST TURNAROUND FOR
POSSIBLE FUTURE WORK

CONCLUSIONS

The four experimental objectives of GATE appear feasible from our preliminary analyses. In addition, the total system also appears feasible. No significant management problem or engineering impediments are foreseen at this time. Technology development's expected in the meteor impact system and the control laws of the command and control system. Current technology will be used in all other areas and many "off-the-shelf" components will be used.

The GATE will add to the body of knowledge of plasma dynamics, tether charging and electroboost. The results will complement the work of TSS-1 and may help plan the second TSS electrodynamic mission. In addition, the GATE will break new ground in the study of micrometeoroid hazards to space tethers. GATE can also provide for more than one set of experiments since it appears to be relatively inexpensive to build and low in integration time. As GATE is a free flyer, safety concerns are minimized.

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